

STRENGTH AND WATER-UP TAKE-RELATED MASS-GAIN RESPONSE OF CEMENT MORTAR MODIFIED WITH 700 °C CORN STRAW ASH AND NaOH-PRETREATED CORN STALK FIBER

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This study investigated cement mortar modified with 700 °C corn straw ash (CSA) and NaOH-pretreated corn stalk fiber (CSF), using natural river sand. CSA contents and CSF volume fractions of 0.5–2.0 vol.% were evaluated through strength tests, water-uptake-related mass gain, replicate statistics, and ANOVA. The highest 7 d flexural and compressive strengths were 6.72 and 34.98 MPa, respectively. At 28 d, A15F1 showed the highest flexural and compressive strengths, 8.37 and 55.67 MPa. CSA, CSF, and their interaction significantly affected strength. Mass gain was treated as a pore-related auxiliary indicator.

Keywords: corn straw ash 1; corn stalk fiber 2; NaOH pretreatment 3; cement mortar strength 4

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1. Introduction

Reducing carbon emissions while maintaining mechanical performance is an important goal in developing cement-based composites. Using agricultural residues in mortar or concrete can help reduce waste disposal pressure and provide alternative raw materials for green building products [1]. In northern China, corn straw is produced in large quantities, but its high-value use as an engineering material still needs further study [2]. Converting plant biomass ash or straw fiber into cement mortar modifiers is therefore a useful way to support agricultural waste recycling and low-carbon construction materials [3].

Corn straw can be used in cement mortar mainly in two forms. One is corn straw ash (CSA), which is obtained by calcination. CSA may affect the cement matrix through filler effects, particle packing, and possible pozzolanic reactions [4]. Previous studies have shown that the performance of agricultural waste ashes depends strongly on raw material source, calcination temperature, grinding

fineness, chemical composition, and curing conditions [5-8]. In addition, alkali oxides, chlorides, and unburned residues in biomass ash may affect the long-term stability of cementitious systems, so chemical composition, strength development, and pore-related behavior should be considered together [9-17].

The other form is corn stalk fiber (CSF), which can improve mortar behavior by bridging cracks, controlling crack growth, and helping stress transfer. The reinforcing effect of natural plant fibers is influenced by fiber type, length, dispersion, water absorption, and fiber–matrix bonding [18-20]. Although plant fibers can improve crack resistance and post-cracking behavior, their hydrophilic nature and durability in alkaline cement environments may also lead to weak interfaces or increased water uptake [21-23]. Therefore, fiber volume fraction and surface treatment are important factors in natural-fiber-reinforced mortar [24-29].

In our previous study, water, CH_3COOH , and NaOH treatments were compared for corn straw fibers used in cement mortar. The results showed that NaOH treatment improved fiber surface characteristics and provided more stable long-term mechanical performance, while CH_3COOH treatment mainly benefited early-age flexural response [30]. Therefore, the present study uses NaOH pretreatment as the fixed fiber treatment method, rather than repeating the full comparison of pretreatment routes.

Based on this background, this study adopts a “preliminary screening–mixed verification” strategy. First, CSA calcined at 600, 700, 800, and 900 °C was compared in terms of chemical composition to clarify the effect of calcination temperature. Then, 700 °C CSA and NaOH -pretreated CSF were selected as the fixed processing route. The effects of CSA replacement level and CSF volume fraction on the 7 d and 28 d flexural strength, compressive strength, and water uptake-related mass gain of natural river sand cement mortar were investigated. Replicate statistics, ANOVA, and model adequacy indicators were used to improve data transparency, and water uptake-related mass gain was used only as a limited pore-related auxiliary indicator, not as direct proof of overall durability improvement.

2. Materials and Methods

2.1 Raw materials and processing route

P·O 42.5 ordinary Portland cement, natural river sand, and tap water were used to prepare cement mortar. Specimen dimensions, molding, and strength testing were conducted with reference to GB/T 17671-2021. The mix proportion followed the standard mortar mass ratio of cement:sand:water = 450:1350:225, but natural river sand was used as the fine aggregate. Additionally, a control batch without any CSA or CSF modifications (designated as A0F0) was fabricated under identical mixing and curing conditions to serve as the reference baseline. The water-to-binder

ratio was 0.50, and the sand-to-binder ratio was 3.00. Corn straw residues were processed through two routes, namely CSA and CSF.

CSA was prepared as follows. Pre-burned corn straw ash was placed in a muffle furnace and calcined under a static air atmosphere. The furnace temperature was increased to the target temperature at a heating rate of 10 °C/min. The straw underwent 2 hours of heat treatment at 600, 700, 800, and 900 °C respectively. After calcination, stop heating so that the ash slag naturally cools down to room temperature in the furnace. The samples were labeled CS600, CS700, CS800, and CS900 according to calcination temperature. The cooled ash was ground using a roller ball mill for 2 h and sieved through a 300 µm sieve to remove coarse particles and improve dispersion in mortar. The preliminary screening stage compared the effect of calcination temperature on ash chemistry and strength activity, while 700 °C CSA was selected as the fixed ash material for the main verification stage.

CSF was prepared by removing the roots, leaves, and pith of corn stalks, retaining only the outer husk. The husks were washed, air-dried, cut into strips, and crushed to obtain coarse fibers. In the preliminary screening stage, boiling-water treatment, CH₃COOH treatment, and NaOH treatment were compared. Based on our previously published study [30] and the present screening results, NaOH-pretreated fibers showed more stable long-term mechanical performance. Therefore, NaOH-pretreated CSF was selected as the fixed fiber route for the verification stage. The fibers were immersed in a 12% NaOH solution at 80 °C for 4 h, washed with clean water until the washing liquid was nearly neutral, and dried to constant mass before use.

The CSF dosage was expressed as the specimen-volume-based volume fraction, with four levels of 0.5, 1.0, 1.5, and 2.0 vol.%. The prism specimen size was 40 mm × 40 mm × 160 mm, corresponding to a volume of 256 cm³. Therefore, 0.5, 1.0, 1.5, and 2.0 vol.% corresponded to fiber volumes of approximately 1.28, 2.56, 3.84, and 5.12 cm³ per specimen, respectively. Because natural fibers have much lower density than cement and sand, volume fraction is more appropriate for discussing fiber dispersion, mass-gain behavior, and mechanical response.

Table 1. Raw materials and processing route.

Item	Main condition	Purpose
Cement	P·O 42.5 ordinary Portland cement, 450 g/batch	Reference binder
Sand	Natural river sand, 1350 g/batch	Fine aggregate
Water	Tap water, 225 g/batch	Mixing water
Water-to-binder ratio	0.50	Control of mixing water
Sand-to-binder ratio	3.00	Reference mortar proportion
Preliminary CSA screening	600, 700, 800 and 900 °C; static air; 10 °C/min; 2 h holding; natural cooling	Selection of ash activation window
Main CSA condition	700 °C; 2 h grinding; 300 µm sieving	Fixed ash treatment for verification

Item	Main condition	Purpose
Preliminary CSF screening	Boiling water, CH ₃ COOH and NaOH treatments	Selection of fiber pretreatment route
Main CSF condition	12% NaOH, 80 °C, 4 h; washed and dried to constant mass	Fiber reinforcement and interface adjustment
CSF volume fraction	0.5, 1.0, 1.5 and 2.0 vol.%	Control of fiber dosage

The CSA samples calcined at 600, 800, and 900 °C and the different fiber pretreatments were used mainly for preliminary screening. Formal replicate statistics, ANOVA, and model evaluation were focused on the 700 °C CSA–NaOH-CSF system with complete specimen-level data. Table 1 summarizes the raw materials and processing route.

2.2 Experimental matrix and specimen preparation

The experimental design consisted of preliminary screening and main mixed verification. The preliminary screening stage justified the selection of 700 °C CSA and NaOH-pretreated CSF. The verification stage used 700 °C CSA and NaOH-CSF as fixed processing conditions and investigated the effects of CSA content and CSF volume fraction on 7 d and 28 d flexural strength, compressive strength, and water-uptake-related mass gain. The CSA replacement levels were 5, 10, 15, and 20% by total binder mass, and the CSF volume fractions were 0.5, 1.0, 1.5, and 2.0 vol.%. Three replicate specimens were prepared for each testing age.

The sample number is in the form of Ax_Fy, A represents the replacement percentage of CSA, and F represents the volume fraction of straw fiber. For example, A10F0.5 represents a mortar sample containing 10% CSA and 0.5 volume percentage straw fiber. Unadded reference samples are marked as A0F0.

The experiment uses 450 g of total rubber, 1350 g of river sand, and 225 g of water as the basic ratio, in which the cement is replaced by 5%~20% CSA proportionally. In the mixing step, first carry out a low-speed dry mixing of cement, CSA, and natural river sand for 30 s. After the base powder is mixed, add the treated CSF and mix for an additional low-speed dry mix for 30 s to break the fiber aggregation and achieve preliminary dispersion. Water was then added, and the mixture was mixed at low speed for 60 s and high speed for 60 s. Manual scraping was performed when necessary to reduce fiber agglomeration.

The fresh mortar was placed into 40 mm × 40 mm × 160 mm triple molds in two layers and compacted using a cement mortar jolting table. The specimens were covered after casting, demolded after 24 h, and immediately cured in water at 20 ± 1 °C until the testing age. Flexural and compressive strength tests were conducted according to GB/T 17671-2021. The broken halves after flexural testing were used for compressive strength testing.

Table 2. Experimental matrix for the 700 °C CSA–NaOH-CSF system.

Factor	Level 1	Level 2	Level 3	Level 4
CSA content/%	5	10	15	20
CSF volume fraction/vol. %	0.5	1.0	1.5	2.0
CSA calcination temperature	700 °C	700 °C	700 °C	700 °C
Fiber treatment	NaOH	NaOH	NaOH	NaOH

² Note: In addition to the 4 × 4 full-factorial experimental matrix, a plain cement mortar group (A0F0) was prepared under the same conditions to act as an external reference baseline.

2.3 Water-uptake-related mass-gain test

To provide a limited pore-related assessment, the mass increase of mortar specimens during water curing was recorded. This index represents mass gain relative to the initial reference mass at different ages, rather than a standard water absorption percentage calculated from oven-dried and saturated specimens. Therefore, it is described as water-uptake-related mass gain or mass-change response. After the sample is removed from the mold, the initial reference mass m_0 is measured immediately, and the sample is placed in water at $20 \pm 1^\circ\text{C}$ for maintenance. In order to track the long-term evolution of water absorption, the specimen is weighed every 2 days during the 28-day test cycle. During the test, you need to quickly use wet wipes to wipe off the free water and immediately reset it to the maintenance environment after completing the reading. The mass increment of each age is determined by equation (1):

$$\Delta m_t = m_t - m_0 \quad (1)$$

where Δm is the mass gain at age t (g), m_t is the surface-dry mass at age t (g), and m_0 is the initial reference mass after demolding (g).

2.4 Data processing and statistical analysis

To improve statistical transparency, the preliminary screening data and main verification data were treated separately. The preliminary screening stage was used only to identify trends in calcination temperature and pretreatment route. Because complete specimen-level replicate records were not retained for all screening groups, the screening data were not used for formal significance testing.

$$CV = \frac{SD}{\bar{x}} \times 100\% \quad (2)$$

where SD is the standard deviation and $\bar{x}$ is the mean value. The 95% confidence interval was calculated using the t distribution, as shown in Eq. (3):

$$95\%CI = \bar{x} \pm t_{0.975, n-1} \times \frac{SD}{\sqrt{n}} \quad (3)$$

where n is the number of replicate specimens, and $n = 3$ in this study. Since both strength and mass-gain data followed a 4×4 full-factorial discrete mixture design, two-way fixed-effect ANOVA was applied to the 28 d responses to evaluate the effects of CSA content, CSF volume fraction, and their interaction. The A0F0

group was utilized as an absolute experimental baseline to evaluate the percentage of strength enhancement or degradation of the modified specimens. Meanwhile, the two-way fixed-effect ANOVA was strictly applied to the 4×4 full-factorial discrete matrix to quantify the independent and interactive effects of CSA content and CSF volume fraction within the modified domain. Model adequacy was assessed using R^2 , adjusted R^2 , predicted R^2 , RMSE, and C.V.

3. Results and Discussion

3.1 Preliminary CSA screening and basis for selecting 700 °C

The chemical composition of CSA changed with calcination temperature. Table 3 summarizes the oxide composition of CSA at different temperatures. The Cl content decreased from 4.41% at 600 °C to 0.91% at 700 °C and further decreased to 0.15% and 0.11% at 800 °C and 900 °C, respectively. Meanwhile, SiO_2 content reached 42.01% at 700 °C, higher than 40.49% at 600 °C, and then slightly decreased at 800 °C and 900 °C.

Table 3. Oxide composition of CSA at different calcination temperatures (%).

Temperature/°C	SiO_2	Al_2O_3	P_2O_5	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cl
600	40.49	0.91	3.85	1.21	10.51	6.03	3.55	26.09	0.44	4.41
700	42.01	1.11	4.44	1.31	11.31	6.51	3.53	21.71	0.89	0.91
800	41.31	1.31	4.54	1.63	11.45	7.51	4.16	20.40	0.72	0.15
900	40.69	1.49	4.85	1.59	12.49	8.36	5.21	21.40	0.55	0.11

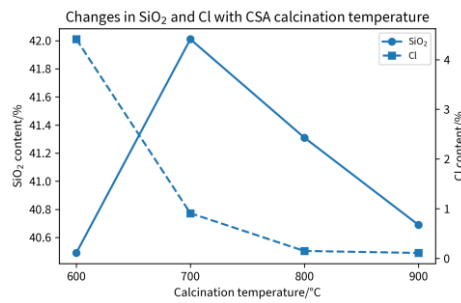


Figure 1. Changes in SiO_2 and Cl with CSA calcination temperature.

Figure 1 indicates that 700 °C provided a reasonable balance between chloride reduction and silica retention. Based on the evolution of early chemical components and the initial screening results of mechanical activity, this study finally selected 700 °C as the standard calcination temperature of CSA, and carried out core verification tests. The remaining temperature gradient data is only used to circle the optimal activation interval, so it is not included in the subsequent analysis of variance and model regression.

3.2 Strength development at 7 d and 28 d

Tables 4 and 5 detail the 7 d and 28 d flexural and compressive strengths for triplicate specimens of each mixture. The reported 95% CIs represent the mean half-width.

Table 4. Replicate statistics of 7 d strength for the 700 °C CSA–NaOH-CSF system.

Code	7 d flexural mean±SD/MPa	CV/%	95%CI	7 d compressive mean±SD/MPa	CV/%	95%CI	n
A0F0	6.20±0.15	-	-	33.10±0.50	-	-	3
A5F0.5	6.35±0.04	0.69	0.11	33.79±0.28	0.83	0.70	3
A5F1	5.72±0.06	0.97	0.14	31.89±0.55	1.72	1.36	3
A5F1.5	6.01±0.13	2.24	0.33	34.98±0.91	2.59	2.25	3
A5F2	5.80±0.05	0.79	0.11	33.84±0.36	1.08	0.90	3
A10F0.5	6.47±0.07	1.11	0.18	31.14±0.73	2.34	1.81	3
A10F1	6.28±0.10	1.59	0.25	30.24±0.10	0.33	0.24	3
A10F1.5	6.14±0.21	3.37	0.51	27.05±0.91	3.36	2.26	3
A10F2	6.13±0.14	2.30	0.35	31.58±0.25	0.80	0.63	3
A15F0.5	5.84±0.03	0.45	0.07	31.69±0.31	0.98	0.77	3
A15F1	5.08±0.14	2.73	0.35	29.35±0.72	2.44	1.78	3
A15F1.5	6.72±0.04	0.54	0.09	31.92±0.62	1.93	1.53	3
A15F2	5.71±0.01	0.18	0.02	34.88±0.37	1.06	0.92	3
A20F0.5	6.54±0.23	3.45	0.56	28.51±0.82	2.89	2.04	3
A20F1	6.02±0.04	0.60	0.09	34.35±0.49	1.41	1.21	3
A20F1.5	6.20±0.19	2.99	0.46	31.21±0.30	0.96	0.75	3
A20F2	5.51±0.04	0.79	0.11	30.35±0.62	2.03	1.53	3

Table 5. Replicate statistics of 28 d strength for the 700 °C CSA–NaOH-CSF system.

Code	28 d flexural mean±SD/MPa	CV/%	95%CI	28 d compressive mean±SD/MPa	CV/%	95%CI	n
A0F0	8.00±0.25	-	-	52.30±0.65	-	-	3
A5F0.5	8.02±0.16	2.00	0.40	49.50±0.55	1.10	1.36	3
A5F1	7.25±0.19	2.62	0.47	51.75±0.35	0.68	0.88	3
A5F1.5	8.08±0.02	0.25	0.05	47.52±0.13	0.26	0.31	3
A5F2	7.73±0.08	1.06	0.20	50.76±1.75	3.46	4.36	3
A10F0.5	7.41±0.22	2.96	0.54	50.66±1.28	2.52	3.17	3
A10F1	8.11±0.17	2.05	0.41	53.26±1.03	1.94	2.57	3
A10F1.5	6.04±0.01	0.17	0.02	49.50±0.47	0.95	1.16	3
A10F2	7.83±0.14	1.80	0.35	47.13±1.10	2.32	2.72	3
A15F0.5	8.13±0.10	1.17	0.24	50.25±2.06	4.10	5.12	3
A15F1	8.37±0.07	0.78	0.16	55.67±0.48	0.86	1.18	3
A15F1.5	8.13±0.07	0.86	0.17	51.13±1.24	2.43	3.08	3
A15F2	7.24±0.11	1.49	0.27	47.98±0.77	1.60	1.90	3
A20F0.5	6.95±0.08	1.12	0.19	54.55±0.42	0.76	1.03	3
A20F1	7.34±0.30	4.09	0.75	50.68±0.35	0.68	0.86	3
A20F1.5	7.75±0.13	1.65	0.32	50.46±1.52	3.01	3.78	3
A20F2	7.74±0.15	1.90	0.37	44.41±0.53	1.20	1.33	3

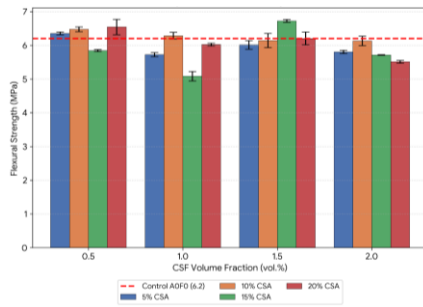


Figure 2. 7 d flexural strength.

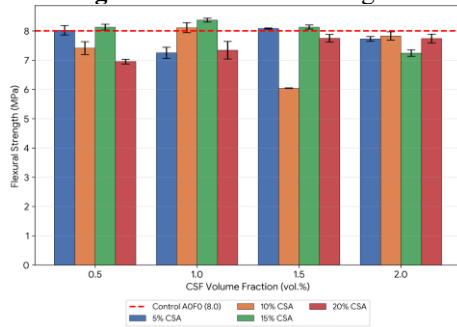


Figure 4. 28 d flexural strength.

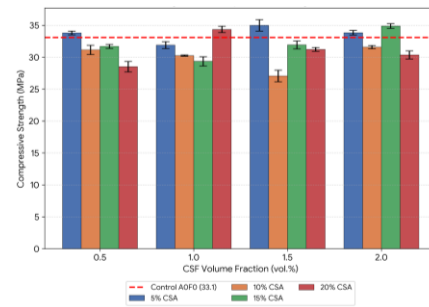


Figure 3. 7 d compressive strength.

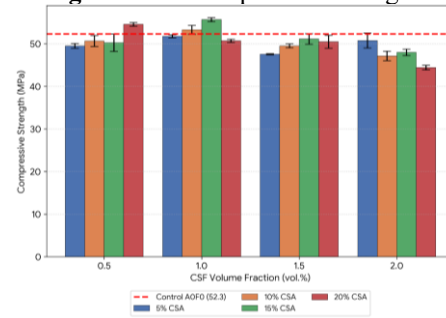


Figure 5. 28 d compressive strength.

In the early 7-day test, the optimized modified group has shown better mechanical properties than the ordinary cement mortar reference group A0F0. Specifically, the 7-day flexural strength of group A15F1.5 was the highest, reaching 6.72 ± 0.04 MPa; while the A5F1.5 group achieved the highest compressive strength of 34.98 ± 0.91 MPa. Taking the flexural strength of 6.20 MPa and the compressive strength of 33.10 MPa in the A0F0 control group as a reference, the two optimal results were improved by 8.39% and 5.68%, respectively.

By 28 d, the synergistic reinforcement of CSA and pretreated CSF became highly pronounced. The optimal A15F1 mixture achieved peak flexural and compressive strengths of 8.37 ± 0.07 MPa and 55.67 ± 0.48 MPa. This performance yielded respective increases of 4.63% and 6.44% over the unmodified baseline values of 8.00 MPa and 52.30 MPa, confirming that combining 700 °C CSA and NaOH-CSF effectively elevates the mechanical limits of green mortar beyond conventional systems.

3.3 ANOVA and model adequacy for 28 d strength

To rigorously quantify the statistical significance and model adequacy, a two-way fixed-effect ANOVA was performed utilizing the complete replicate dataset at 28 d. The CSA replacement level and CSF volume fraction were assigned as fixed factors, with the interaction effect between CSA and CSF explicitly evaluated.

Table 6. Two-way ANOVA results for 28 d strength.

Response	Source	SS	df	MS	F-value	p-value
Flexural	CSA	2.970	3	0.990	48.19	<0.0001
Flexural	CSF	0.430	3	0.143	6.97	0.0010
Flexural	CSA × CSF	11.986	9	1.332	64.82	<0.0001
Flexural	Error	0.657	32	0.021	—	—
Compressive	CSA	14.286	3	4.762	4.45	0.0101
Compressive	CSF	182.457	3	60.819	56.84	<0.0001
Compressive	CSA × CSF	157.519	9	17.502	16.36	<0.0001
Compressive	Error	34.242	32	1.070	—	—

Table 7. Model adequacy indicators for 28 d strength.

Response	R ²	Adjusted R ²	Predicted R ²	RMSE	C.V./%
Flexural	0.9590	0.9398	0.9078	0.143	1.88
Compressive	0.9119	0.8705	0.8017	1.034	2.06

The ANOVA results indicate that the CSA replacement level, CSF volume fraction, and their interaction all exerted highly significant effects on both flexural and compressive strengths at 28 d ($P < 0.05$). Regarding model adequacy, the R^2 , adjusted R^2 , and predicted R^2 for flexural strength were 0.9590, 0.9398, and 0.9078, respectively; the corresponding values for compressive strength were 0.9119, 0.8705, and 0.8017. These metrics confirm that the two-way full-factorial model can adequately explain the vast majority of the variance within the experimental domain.

3.4 Water-uptake-related mass gain and mass-change response

Based on the mass increase behavior of the specimen during the maintenance period of 2~28 d, this paper makes a preliminary discussion on its pore-related characteristics. In view of the fact that the test result is superimposed on both the adsorption of free water and the mass fluctuation of the matrix hydration process, the study defines it as a relative evaluation index.

Table 8. Replicate statistics of 28 d water-uptake-related mass gain.

Code	28 d mass gain mean±SD/g	CV/%	95%CI/g	n
A5F0.5	2.90±0.04	1.50	0.11	3
A5F1	3.06±0.05	1.48	0.11	3
A5F1.5	3.38±0.05	1.34	0.11	3
A5F2	4.07±0.07	1.72	0.17	3
A10F0.5	2.94±0.03	0.86	0.06	3
A10F1	2.88±0.08	2.91	0.21	3
A10F1.5	5.39±0.07	1.32	0.18	3
A10F2	3.88±0.09	2.19	0.21	3
A15F0.5	3.05±0.13	4.29	0.32	3
A15F1	3.09±0.03	0.93	0.07	3
A15F1.5	4.46±0.07	1.49	0.17	3
A15F2	3.45±0.08	2.42	0.21	3

A20F0.5	3.14±0.03	0.84	0.07	3
A20F1	2.56±0.08	3.18	0.20	3
A20F1.5	3.64±0.02	0.42	0.04	3
A20F2	4.02±0.04	0.87	0.09	3

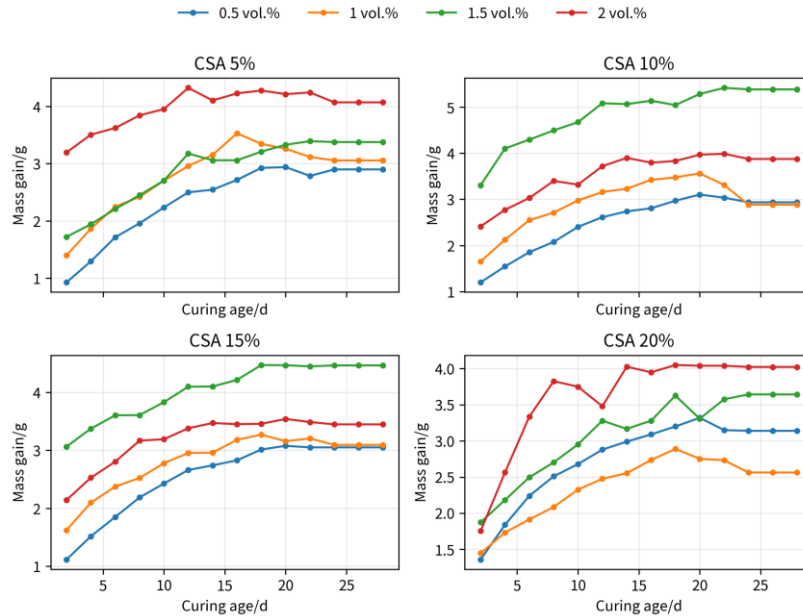


Figure 6. Effect of CSF content on mass gain at different CSA levels.

Table 9. Two-way ANOVA results for 28 d mass gain.

Source	SS	df	MS	F-value	p-value
CSA	1.446	3	0.482	111.89	<0.0001
CSF	14.934	3	4.978	1155.99	<0.0001
CSA × CSF	7.306	9	0.812	188.52	<0.0001
Error	0.138	32	0.004	—	—

Table 10. Model adequacy indicators for mass gain.

Response	R ²	Adjusted R ²	Predicted R ²	RMSE/g	C.V./%
28 d mass gain	0.9942	0.9915	0.9870	0.066	1.88

As shown in Figure 6, the mass increment of each group of specimens generally tends to increase with the extension of the maintenance period, showing the typical evolutionary characteristics of "early surge and later slowdown". By 28 d, the water absorption weight gain of group A10F1.5 reached the highest value of 5.39 ± 0.07 g, while the A20F1 group recorded the lowest value of 2.56 ± 0.08 g. As mentioned above, a high weight gain cannot be simply equivalent to the deterioration of durability; it is essentially a macrophysical expression of the three effects of fiber's own hydrophilicity, internal pore connection network, and matrix hydration water consumption.

The analysis of the variance of 28 d mass changes confirmed that the CSA adsorption, CSF volume fraction, and their interactions were all statistically significant, and their p-values were less than 0.05. It should be especially noted that the F value corresponding to the main effect of CSF is the largest, which means that the amount of fiber added plays a decisive role in the absorption and weight gain behavior of the dominant system. The decisive coefficients R^2 , adjusted R^2 , and predicted R^2 of the model are as high as 0.9942, 0.9915, and 0.9870, respectively. Combined with the coefficient of variation of only 1.88%, it fully verifies its powerful explanatory power for data fluctuations within the experimental design range.

4. Practical implications, limitations, and future work

The results indicate that the combined use of 700 °C corn straw ash and NaOH-pretreated corn stalk fiber can be a feasible way to reuse corn straw residues in cement mortar. Within the tested range, some mixtures showed improved flexural and compressive strengths compared with the plain reference mortar. At 28 d. This suggests that a suitable combination of CSA content and CSF volume fraction may improve the strength response of natural river sand cement mortar while reducing part of the cement consumption.

However, the mass-gain test reflects water-curing-related mass change and pore-related behavior, but it is not the same as standard water absorption or direct proof of overall durability improvement. Future work should include SEM, XRD, FTIR, pore-structure analysis, and long-term durability tests to verify the interfacial mechanism and service performance further.

5. Conclusions

This study systematically confirmed that the CSF pretreated with CSA and NaOH calcinated at 700 °C, in the natural river sand cement mortar can effectively improve the physical and mechanical properties of the matrix. The main research results are summarized as follows:

Within the tested temperature range, CSA calcined at 700 °C showed a suitable balance between SiO_2 content and Cl reduction. The SiO_2 content reached 42.01%, and the Cl content decreased to 0.91%. Therefore, 700 °C CSA was selected as the fixed ash condition for the main verification stage, but it should not be regarded as a universal optimum temperature for all corn straw ashes.

The modified composite mortar demonstrated significant long-term structural advantages over the unmodified A0F0 baseline. At 7 d, the system achieved maximum respective increases of 8.39% and 5.68% in flexural and compressive strengths. By 28 d, the synergistic reinforcement of CSA and pretreated CSF was fully realized. The optimal A15F1 mixture recorded a 4.63%

increase in flexural strength, while its compressive strength climbed to 55.67 MPa, representing a 6.44% improvement over the baseline value of 52.30 MPa.

Building a modification system for CSA collaborative pretreatment CSF provides a potential environmental protection path to break through the bottleneck of mechanical properties of green cement-based materials. In the future, the work will focus on the characteristics of the micro-interface transition zone of the composite system and the long-term durability boundary in harsh environments.

Author Contributions

Conceptualization, B.P. and H.L.; methodology, B.P.; validation, B.P., K.L. and M.Z.; formal analysis, B.P.; investigation, B.P. and K.L.; resources, H.L. and M.Z.; data curation, B.P.; writing—original draft preparation, B.P.; writing—review and editing, H.L., K.L. and M.Z.; visualization, B.P.; supervision, H.L.; project administration, B.P.; funding acquisition, B.P. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

All data presented and analyzed in this manuscript, including all experimental results, figures, and tables that support the conclusions of this study, are publicly available within the published article. Additional underlying raw experimental files and extended datasets are not publicly available due to institutional confidentiality restrictions.

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Conflicts of Interest

The authors declare no conflict of interest.

Artificial Intelligence Disclosure

No artificial intelligence-based or generative tools were used in the preparation of this manuscript.

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