Supporting Information

Laboratory Study on the Use of Urease-Induced Calcium Carbonate Precipitation for Stabilization of Coal Fly Ash

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The Supporting Information has 13 pages, including additional details of methods, Supplemental Figures S1-S2, and Supplemental Table S1-S5.

Methods

UCS

The SLB-1 stress-strain controlled triaxial shear penetration tester (manufactured by Nanjing Soil Instrument Factory Co., Ltd.) was used to simulate the UCS. The measuring indenter was a flat head with a cross-sectional area of about 10 cm^2, which compressed the sample at a strain rate of 0.5 mm/min, read, and recorded the peak pressure value.

Shaking and Sieving

In order to evaluate the curing effect of different treatment solutions on the FA particles, a shaking and sieving test was taken out for the cured samples. The test was conducted using a GS-86 electric vibrating sieve machine (manufactured by Shangyu City Sieve Factory, Zhejiang Province) with a standard

inspection sieve of 0.5 mm, 1.46 mm, and 2.5 mm. The speeds of the sieve vibrations were 1400 rpm, and the vibration lasted 15 minutes. The percentage of samples of various particle sizes was weighed in the end.

Wind-tunnel test

The sample was placed on the bottom frame of the wind tunnel, which was fixed on a slope of 10°. The total length of the wind tunnel machine was 60 cm, and the cross-section was 40 × 25 cm^2. The mass change of the sample was evaluated under the wind speed of 10 m/s for 18 minutes, and the results were accurate to 0.001 mg. The formula (1) was used to calculate the wind erosion rate E.

$$E=(m_0-m_1)/(s\cdot t) \quad (1)$$

Where E is the wind erosion rate, mg/(m^2·min); m_0 is the mass of FA before wind erosion, mg; m_1 is the mass of FA after wind erosion, mg; s is the surface area of the sample, m^2; t is the wind erosion time, min.

X-ray diffraction (XRD) analysis

XRD analysis was used to identify the mineral composition of FA. The samples were scanned continuously using Smart lab (RIKEN, Japan) with a scanning speed of 10°/min, and the 2θ correction value was equal to 0.002°.

Chemical component analysis

The chemical composition analysis of major elements and trace elements of the FA samples was completed at the Analytical Laboratory Beijing

Research Institute of Uranium Geology. The major elements were determined by XRF (Panaco Axios^{MAX}) method, according to standard GB/T14506.28-2010, and the loss on ignition standard was GB/T14506.34-2019, with an analysis accuracy of 5%. Trace elements were determined using an ELEMENT XR plasma mass spectrometer, following standard GB/T 14506.30-2010, and the relative standard deviation was less than 5%.

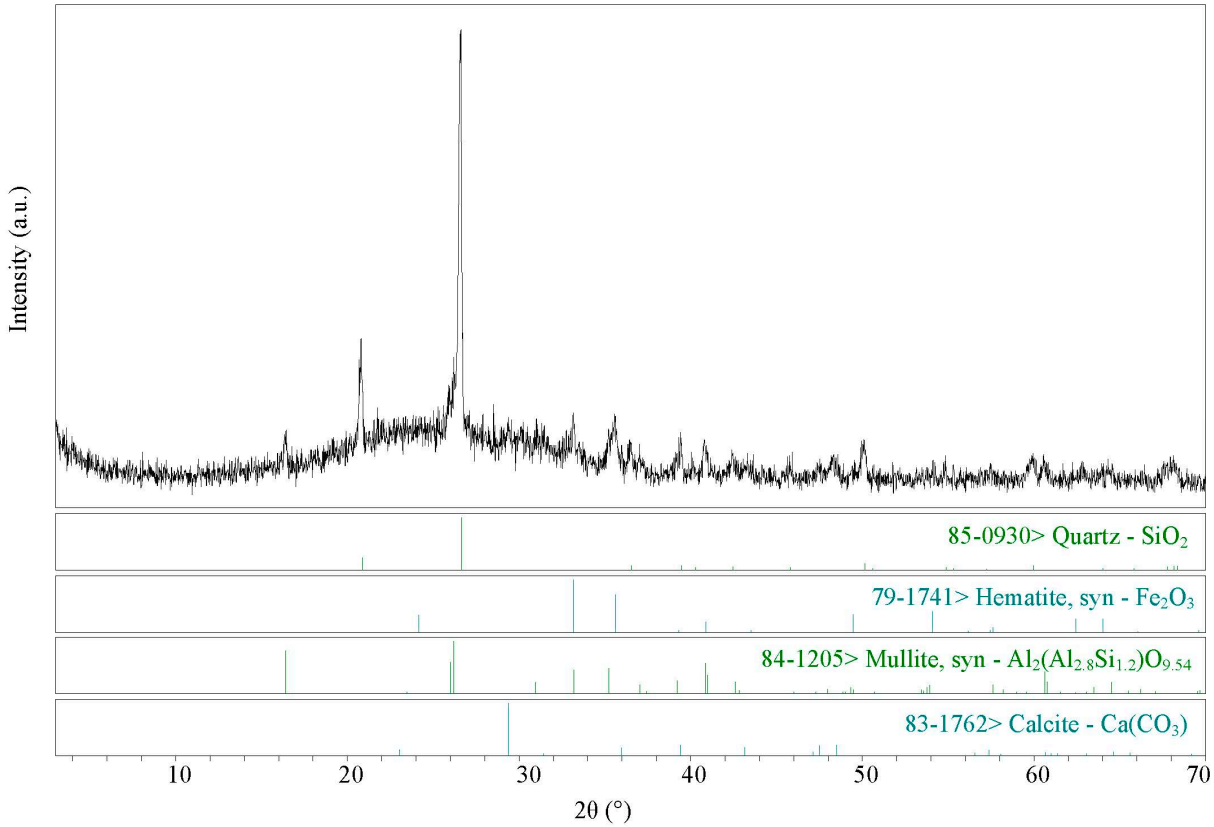

Fig. S1 XRD patterns of fly ash.

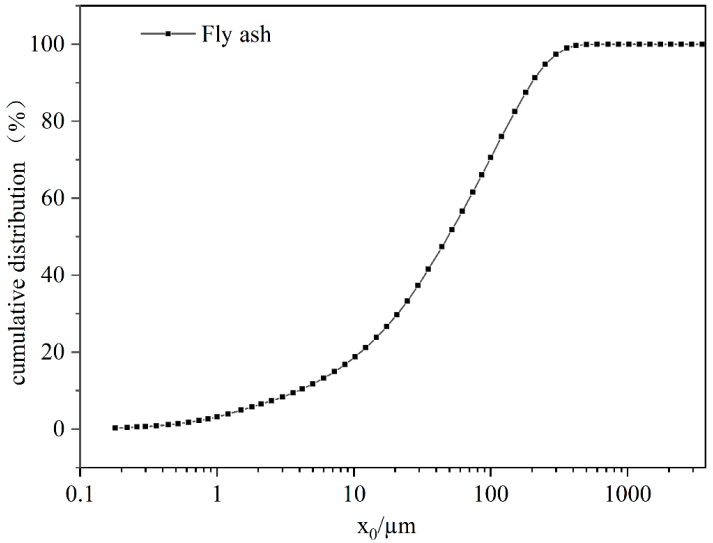

Fig. S2 Particle size distribution curve of fly ash.

Table S1. Major element (*wt* %) and trace element (μg/g) compositions of fly ash.

Major elements (%)											
SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	TiO_2	P_2O_5	loss on ignition	FeO
56.32	21.67	4.92	2.15	8.97	1.41	1.64	0.053	1.02	0.09	1.73	1.95
Trace elements (μg/g)											
Li	Be	Sc	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr
31.7	3.98	31.7	135	92.2	191	28.4	79.5	50.6	24.8	89.6	1723
Y	Mo	Cd	In	Sb	Cs	Ba	La	Ce	Pr	Nd	Sm
75.7	3.72	0.299	0.103	2.25	14.4	963	66.2	124	15.8	67.5	12
Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	W	Re	Tl
2.93	10.5	2.28	13	2.78	7.56	1.34	9.46	1.28	941	0.01	0.696
Pb	Bi	Th	U	Nb	Ta	Zr	Hf				
45	0.746	27	8.01	14.2	1.62	242	7.92				

Table S2. Unconfined compressive strength of samples cured with different treatment solutions

No.	Composition	Maintenance conditions	Unconfined compressive strength (kPa)			Average (kPa)	Minimum (kPa)	Maximum (kPa)	Standard deviation
			sample1	sample2	sample3				
1	U	Standard							
2	T-0-0-0-0	Standard	42.7	40.6	40.6	41.3	40.6	42.7	1.2
3	T-1-0.3-4.6-0	Standard	348.6	350.0	346.5	348.4	346.5	350.0	1.8
4	T-1-0.3-46-0	Standard	398.3	389.9	390.5	392.9	389.9	398.3	4.7
5	T-1-0.3-92-0	Standard	537.6	540.4	544.6	540.9	537.6	544.6	3.5
6	T-1-0.3-138-0	Standard	575.4	578.9	579.6	578.0	575.4	579.6	2.3

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7	T-1-0.3-460-0	Standard	690.9	696.5	696.5	694.6	690.9	696.5	3.2
8	T-1-0.3-920-0	Standard	743.4	749.7	752.5	748.5	743.4	752.5	4.7
9	T-0-0-460-0	Standard	44.8	47.6	48.3	46.9	44.8	48.3	1.9
10	T-1-0-460-0	Standard	193.2	186.9	186.9	189.0	186.9	193.2	3.6
11	T-0.3-0.3-460-0	Standard	352.8	345.1	346.5	348.1	345.1	352.8	4.1
12	T-0.6-0.3-460-0	Standard	562.1	557.2	556.5	558.6	556.5	562.1	3.1
13	T-1.5-0.3-460-0	Standard	603.4	606.2	604.2	604.6	603.4	606.2	1.4
14	T-2-0.3-460-0	Standard	431.9	434.0	432.6	432.8	431.9	434.0	1.1
15	T-0-0-0-0.6	Standard	364.7	368.9	369.6	367.7	364.7	369.6	2.7
16	T-1-0.3-0-0.6	Standard	378.7	377.3	375.9	377.3	375.9	378.7	1.4
17	T-1-0.3-4.6-0.6	Standard	526.4	519.4	520.1	522.0	519.4	526.4	3.9
18	T-1-0.3-46-0.6	Standard	561.4	553.7	555.8	557.0	553.7	561.4	4.0
19	T-1-0.3-92-0.6	Standard	912.8	905.1	906.5	908.1	905.1	912.8	4.1
20	T-1-0.3-138-0.6	Standard	899.5	900.9	902.3	900.9	899.5	902.3	1.4
21	T-1-0.3-460-0.6	Standard	911.4	916.3	905.1	910.9	905.1	916.3	5.6
22	T-1-0.3-920-0.6	Standard	938.0	936.6	943.6	939.4	936.6	943.6	3.7
2	T-0-0-0-0	Wet-dry cycle	59.5	58.1	59.5	59.0	58.1	59.5	0.8
10	T-1-0-460-0	Wet-dry cycle	197.4	202.3	205.7	201.8	197.4	205.7	4.2
7	T-1-0.3-460-0	Wet-dry cycle	463.4	473.9	467.6	468.3	463.4	473.9	5.3
15	T-0-0-0-0.6	Wet-dry cycle	263.9	265.3	268.8	266.0	263.9	268.8	2.5
21	T-1-0.3-460-0.6	Wet-dry cycle	649.6	649.6	658.0	652.4	649.6	658.0	4.8
2	T-0-0-0-0	Freeze-thaw cycle							
10	T-1-0-460-0	Freeze-thaw cycle							
7	T-1-0.3-460-0	Freeze-thaw cycle	428.4	434.7	431.5	431.5	428.4	434.7	2.6
15	T-0-0-0-0.6	Freeze-thaw cycle	74.9	79.8	87.5	80.7	74.9	87.5	2.5
21	T-1-0.3-460-0.6	Freeze-thaw cycle	479.5	488.6	488.6	485.6	479.5	488.6	4.3

Table S3. Particle size distribution of the agglomerates formed by the solidification of fly ash with different solutions

No.	Composition	Maintenance conditions	The total mass of the sample (g)	Mass of sample with different particle size (g)				Percentage of the sample with different particle size			
				≥2.5mm	2.5-1.46mm	1.46-0.5mm	≥0.5mm	≥2.5mm	2.5-1.46mm	1.46-0.5mm	≥0.5mm
1	U	Standard									
2	T-0-0-0-0	Standard	97.637	0	0	0.201	0.201	0	0	0.21%	0.21%
3	T-1-0.3-4.6-0	Standard	100.985	0	0	0.822	0.822	0	0	0.81%	0.81%
4	T-1-0.3-46-0	Standard	100.450	0	0	1.031	1.031	0	0	1.03%	1.03%
5	T-1-0.3-92-0	Standard	101.314	0	0	1.309	1.309	0	0	1.29%	1.29%
6	T-1-0.3-138-0	Standard	101.161	0	0	1.476	1.476	0	0	1.46%	1.46%
7	T-1-0.3-460-0	Standard	100.836	0	0	1.553	1.553	0	0	1.54%	1.54%
8	T-1-0.3-920-0	Standard	100.524	0	0	1.652	1.652	0	0	1.64%	1.64%
9	T-0-0-460-0	Standard	95.671	0	0	0.229	0.229	0	0	0.24%	0.24%
10	T-1-0-460-0	Standard	100.670	0	0	0.356	0.356	0	0	0.35%	0.35%
11	T-0.3-0.3-460-0	Standard	100.774	0	0	1.424	1.424	0	0	1.41%	1.41%
12	T-0.6-0.3-460-0	Standard	101.349	0	0	1.455	1.455	0	0	1.44%	1.44%
13	T-1.5-0.3-460-0	Standard	101.833	0	0	1.533	1.533	0	0	1.51%	1.51%
14	T-2-0.3-460-0	Standard	101.957	0	0.049	1.459	1.508	0	0.05%	1.43%	1.48%
15	T-0-0-0-0.6	Standard	99.979	0	0	0.540	0.540	0	0	0.54%	0.54%
16	T-1-0.3-0-0.6	Standard	102.863	0	0	0.727	0.727	0	0	0.71%	0.71%
17	T-1-0.3-4.6-0.6	Standard	102.886	7.504	0.598	11.756	19.858	7.29%	0.58%	11.43%	19.30%
18	T-1-0.3-46-0.6	Standard	101.893	8.578	1.006	10.670	20.254	8.42%	0.99%	10.47%	19.88%
19	T-1-0.3-92-0.6	Standard	100.698	9.415	1.431	9.853	20.699	9.35%	1.42%	9.78%	20.56%
20	T-1-0.3-138-0.6	Standard	102.36	10.169	1.744	9.561	21.474	9.93%	1.70%	9.34%	20.98%
21	T-1-0.3-460-0.6	Standard	102.133	12.866	2.404	6.193	21.463	12.60%	2.35%	6.06%	21.01%
22	T-1-0.3-920-0.6	Standard	102.749	12.973	2.898	6.057	21.928	12.63%	2.82%	5.89%	21.34%

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2	T-0-0-0-0	Wet-dry cycle	98.027	0	0	0.225	0.225	0	0	0.23%	0.23%
10	T-1-0-460-0	Wet-dry cycle	99.607	0	0	0.389	0.389	0	0	0.39%	0.39%
7	T-1-0.3-460-0	Wet-dry cycle	100.265	0	0	0.659	0.659	0	0	0.66%	0.66%
15	T-0-0-0-0.6	Wet-dry cycle	99.586	0	0	0.464	0.464	0	0	0.47%	0.47%
21	T-1-0.3-460-0.6	Wet-dry cycle	101.325	2.944	0.319	2.736	5.999	2.91%	0.31%	2.70%	5.92%
2	T-0-0-0-0	Freeze-thaw cycle	95.856	0	0	0.117	0.117	0	0	0.12%	0.12%
10	T-1-0-460-0	Freeze-thaw cycle	99.789	0	0	0.274	0.274	0	0	0.27%	0.27%
7	T-1-0.3-460-0	Freeze-thaw cycle	99.68	0	0	0.634	0.634	0	0	0.64%	0.64%
15	T-0-0-0-0.6	Freeze-thaw cycle	99.665	0	0	0.341	0.341	0	0	0.34%	0.34%
21	T-1-0.3-460-0.6	Freeze-thaw cycle	101.922	1.983	0.753	2.402	5.138	1.95%	0.74%	2.36%	5.04%

Table S4. Wind erosion rate of samples treated with different solutions (mg/(m²·min))

No.	Composition	Maintenance conditions	sample1	sample2	sample3	Average	Minimum	Maximum	Standard deviation
1	U	Standard	39.745	40.421	38.536	39.567	38.536	40.421	0.955
2	T-0-0-0-0	Standard	5.742	5.824	5.880	5.815	5.742	5.880	0.069
3	T-1-0.3-4.6-0	Standard	3.564	3.669	3.462	3.565	3.462	3.669	0.104
4	T-1-0.3-46-0	Standard	3.311	3.285	3.307	3.301	3.285	3.311	0.014
5	T-1-0.3-92-0	Standard	2.872	2.904	2.939	2.905	2.872	2.939	0.034
6	T-1-0.3-138-0	Standard	2.701	2.619	2.543	2.621	2.543	2.701	0.079
7	T-1-0.3-460-0	Standard	2.221	2.219	2.008	2.149	2.008	2.221	0.122
8	T-1-0.3-920-0	Standard	1.966	1.975	2.018	1.986	1.966	2.018	0.028
9	T-0-0-460-0	Standard	5.556	5.607	5.752	5.638	5.556	5.752	0.102
10	T-1-0-460-0	Standard	4.982	4.970	4.957	4.970	4.957	4.982	0.013
11	T-0.3-0.3-460-0	Standard	2.847	2.799	2.900	2.849	2.799	2.900	0.051
12	T-0.6-0.3-460-0	Standard	2.514	2.507	2.497	2.506	2.497	2.514	0.009
13	T-1.5-0.3-460-0	Standard	2.190	2.172	2.195	2.186	2.172	2.195	0.012
14	T-2-0.3-460-0	Standard	2.391	2.405	2.385	2.394	2.385	2.405	0.010
15	T-0-0-0-0.6	Standard	3.125	2.997	2.921	3.014	2.921	3.125	0.103
16	T-1-0.3-0-0.6	Standard	3.012	2.894	3.104	3.003	2.894	3.104	0.105
17	T-1-0.3-4.6-0.6	Standard	2.649	2.728	2.840	2.739	2.649	2.840	0.096
18	T-1-0.3-46-0.6	Standard	2.385	2.416	2.371	2.391	2.371	2.416	0.023
19	T-1-0.3-92-0.6	Standard	1.968	1.999	2.009	1.992	1.968	2.009	0.021
20	T-1-0.3-138-0.6	Standard	1.745	1.786	1.914	1.815	1.745	1.914	0.088
21	T-1-0.3-460-0.6	Standard	1.536	1.496	1.544	1.525	1.496	1.544	0.026
22	T-1-0.3-920-0.6	Standard	1.484	1.455	1.427	1.455	1.427	1.484	0.029
2	T-0-0-0-0	Wet-dry cycle	5.701	6.012	5.514	5.742	5.514	6.012	0.252
10	T-1-0-460-0	Wet-dry cycle	4.897	4.942	4.961	4.933	4.897	4.961	0.033
7	T-1-0.3-460-0	Wet-dry cycle	2.642	2.573	2.488	2.568	2.488	2.642	0.077

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15	T-0-0-0-0.6	Wet-dry cycle	3.412	3.371	3.322	3.368	3.322	3.412	0.045
21	T-1-0.3-460-0.6	Wet-dry cycle	1.718	1.599	1.512	1.610	1.512	1.718	0.103
2	T-0-0-0-0	Wet-dry cycle	10.725	10.496	10.435	10.552	10.435	10.725	0.153
10	T-1-0-460-0	Wet-dry cycle	7.004	7.010	6.923	6.979	6.923	7.010	0.049
7	T-1-0.3-460-0	Wet-dry cycle	2.687	2.985	2.680	2.784	2.680	2.985	0.174
15	T-0-0-0-0.6	Wet-dry cycle	3.962	3.999	4.192	4.051	3.962	4.192	0.124
21	T-1-0.3-460-0.6	Wet-dry cycle	1.918	2.014	1.774	1.902	1.774	2.014	0.121

Table S5. Percentages of elements in FA before and after being treated with EICP

Element	Line type	Virgin FA		EICP		EICP-PAM	
		Percentage of weight %	Percentage of atom %	Percentage of weight %	Percentage of atom %	Percentage of weight %	Percentage of atom %
O	K	49.54	63.24	22.95	35.66	56.04	59.49
Si	K	22.51	16.37	7.24	6.41	7.96	4.81
Al	K	9.1	6.89	1.83	1.68	6.47	4.08
Fe	L	3.93	1.44	2.45	1.09	2.32	0.71
Ca	K	4.86	2.48	51.02	31.64	1.97	0.84
C	K	2.94	5.01	10.27	21.05	16.21	22.92
N	K	0	0	1.07	1.14	3.57	4.32
Na	K	2.03	1.8	0.28	0.31	0.84	0.62
Mg	K	0.97	0.81	0.27	0.28	1.09	0.76
K	K	1.96	1.02	0.11	0.07	0.11	0.05
Ti	K	0.88	0.38	0	0	0	0
Co	L	0.12	0.04	0.26	0.11	0	0
Ni	L	0	0	0.05	0.02	0	0
S	K	0.07	0.04	0.41	0.27	0.39	0.21
Cl	K	0.68	0.39	0.2	0.09	2.15	1.03
As	L	0.01	0	0	0	0	0
Zn	L	0.05	0.02	0	0	0.06	0.02
Mo	L	0.36	0.08	0	0	0.82	0.14
Cd	L	0	0	0	0	0	0
Hg	M	0	0	0.19	0.02	0	0
Pb	M	0	0	1.4	0.17	0	0
Total		100	100	100	100	100	100