Replacement of biochar from waste for cement: mechanisms and eco-benefits

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Supplementary file 1-A Variance analysis of three-class concrete with different replacement of PPMS for cement

Concrete grades	Mechanical indexes	Variance sources	Sum of squares	Free degree	Mean squares	F	P-value
C20	Compressive strength	SA	193.71	8	24.21	4.7	0.003
		SE	92.78	18	5.16		
		ST	286.49	26			
	Flexural strength	SA	13.42	8	1.68	13.48	0
		SE	2.24	18	0.12		
		ST	15.66	26			
	Splitting tensile strength	SA	2.84	8	0.36	6.38	0.001
		SE	1	18	0.06		
		ST	3.84	26			
C30	Compressive strength	SA	416.91	8	53.22	12.31	0
		SE	76.2	18	4.23		
		ST	493.10	26			
	Flexural strength	SA	7.93	8	0.92	1.71	0.16
		SE	10.37	18	0.58		
		ST	18.3	26			
	Splitting tensile strength	SA	5.07	8	0.63	13.25	0
		SE	0.86	18	0.048		
		ST	5.93	26			
C40	Compressive strength	SA	302.99	8	37.87	5.95	0.01
		SE	114.65	18	6.37		
		ST	417.63	26			
	Flexural strength	SA	14.86	8	1.86	2.32	0.07
		SE	14.43	18	0.80		
		ST	29.29	26			
	Splitting tensile strength	SA	2.11	8	0.263	10.50	0
		SE	0.45	18	0.025		
		ST	2.56	26			

Supplementary file 1-B Variance analysis of three-class concrete with different replacement of PPDG for cement

Concrete grades	Mechanical indexes	Variance sources	Sum of squares	Free degree	Mean squares	F	Significance
C40	Compressive strength	SA	1435.35	8	179.42	36.54	0.00
		SE	88.38	18	4.91		
		ST	1523.73	26			
	Flexural strength	SA	4.52	8	0.56	11.98	0.00
		SE	0.85	18	0.05		
		ST	5.37	26			
	Splitting tensile	SA	5.62	8	0.70	19.81	0.00
		SE	0.64	18	0.04		

	strength	ST	6.26	26			
C30	Compressive strength	SA	1291.44	8			
		SE	43.17	18	161.43 2.40	67.32	0.00
		ST	1334.61	26			
	Flexural strength	SA	2.82	8			
		SE	0.77	18	0.35 0.04	8.30	0.00
		ST	3.59	26			
	Splitting tensile strength	SA	3.26	8			
		SE	0.20	18	0.41 0.01	36.44	0.00
		ST	3.46	26			
C20	Compressive strength	SA	415.72	8			
		SE	35.47	18	51.97 1.97	26.37	0.00
		ST	451.20	26			
	Flexural strength	SA	2.03	8			
		SE	1.74	18	0.25 0.10	2.63	0.04
		ST	3.77	26			
	Splitting tensile strength	SA	4.06	8	0.51 0.04	13.37	0.00

Supplementary file 2

For PPMS:

A: Difference in the loss of mass from PPMS concretes among the groups of after 25, 50, 75 and 100 freeze-thaw cycles. Each group included the strongest and weakest groups of C20, C30 and C40 concrete specimen (in which 1-30% cement was replaced by PPMS) in compressive strength and control group (in which no cement was replaced).

Variance source	Sum of squares	df	Root mean square	F	Significance
S_A	0.713	3	0.238	0.715	0.545
S_E	34.575	104	0.332		
S_T	35.288	107			

B: Difference in the loss of mass among the strongest and weakest groups of C20 PPMS concrete specimens and control group in compressive strength after 25, 50, 75 and 100 times of freeze-thaw cycle.

Number of freeze-thaw cycles	Variance source	Sum of squares	df	Root mean square	F	Significance
25	S_A	0.046	2	0.023	5.273	0.048
	S_E	0.026	6	0.004		
	S_T	0.073	8			
50	S_A	0.104	2	0.052	7.544	0.023
	S_E	0.041	6	0.007		
	S_T	0.145	8			
70	S_A	1.278	2	0.639	0.191	0.831
	S_E	20.066	6	3.344		
	S_T	21.344	8			
100	S_A	0.200	2	0.100	9.261	0.015
	S_E	0.065	6	0.011		
	S_T	0.265	8			

C: Difference in the loss of mass among the strongest and weakest groups of C30 PPMS concrete specimens and control group in compressive strength after 25, 50, 75 and 100 times of freeze-thaw cycle.

Number of freeze-thaw cycles	Variance source	Sum of squares	df	Root mean square	F	Significance
25	S_A	0.011	2	0.006	6.372	0.033
	S_E	0.005	6	0.001		
	S_T	0.017	8			
50	S_A	0.014	2	0.007	3.120	0.118
	S_E	0.014	6	0.002		
	S_T	0.028	8			
	S_A	3.356	2	1.678	2.580	0.155

70	S_E	3.902	6	0.650		
	S_T	7.258	8			
100	S_A	0.373	2	0.186	1.664	0.266
	S_E	0.672	6	0.112		
	S_T	1.045	8			

D: Difference in the loss of mass among the strongest and weakest groups of C40 PPMS concrete specimens and control group in compressive strength after 25, 50, 75 and 100 times of freeze-thaw cycle.

Number of freeze-thaw cycles	Variance source	Sum of squares	df	Root mean square	F	Significance
25	S_A	0.061	2	0.030	2.664	0.163
	S_E	0.057	5	0.011		
	S_T	0.118	7			
50	S_A	0.202	2	0.101	19.629	0.002
	S_E	0.031	6	0.005		
	S_T	0.233	8			
70	S_A	0.183	2	0.092	99.964	0.000
	S_E	0.005	6	0.001		
	S_T	0.189	8			
100	S_A	0.247	2	0.124	1.556	0.285
	S_E	0.477	6	0.079		
	S_T	0.724	8			

E: Difference in the compressive-strength of PPMS concretes between all groups of before and after 100 freeze-thaw cycles. These groups included the strongest and weakest groups of C20, C30 and C40 concrete specimen (in which 1-30% cement was replaced by PPMS) and control group (in which no cement was replaced)

Variance source	Sum of squares	df	Root mean square	F	Significance
S_A	310.564	1	310.564	4.851	.032
S_E	3201.372	52	64.027		
S_T	3511.935	53			

F: Difference in the compressive strength among the strongest and weakest groups of PPMS concretes (in which 1-30% cement was replaced by PPMS) and their control group (in which no cement was replaced) before and after 100 freeze-thaw cycles

Freeze-thaw cycle	Concrete class	Variance source	Sum of squares	df	Root mean square	F	Significance
Before	C20	S_A	248.869	2	124.434	10.742	$P < 0.05$
		S_E	69.502	6	11.584		
		S_T	318.370	8			
		S_A	53.695	2	26.847	1.236	$P > 0.05$

	C30	S_E	130.343	6	21.724		
		S_T	184.038	8			
	C40	S_A	89.974	2	44.987	8.866	P < 0.05
		S_E	30.445	6	5.074		
		S_T	120.419	8			
After	C20	S_A	152.05	2	76.025	22.571	P < 0.01
		S_E	20.210	6	3.368		
		S_T	172.260	8			
	C30	S_A	68.987	2	34.494	5.776	P > 0.05
		S_E	35.833	6	5.972		
		S_T	104.820	8			
	C40	S_A	124.647	2	6.074	10.261	P < 0.05
		S_E	36.443	6	62.324		
		S_T	161.090	8			

For PPDG

G: Difference in the loss of mass from PPDG concretes among the groups of after 25, 50, 75 and 100 freeze-thaw cycles. Each group included the strongest and weakest groups of C20, C30 and C40 concrete specimen (in which 1-30% cement was replaced by PPDG) in compressive strength and control group (in which no cement was replaced).

Variance source	Sum of squares	df	Root mean square	F	Significance
S_A	0.749	3	0.000	61.716	0.000
S_E	0.421	104	0.249		
S_T	1.170	107			

H: Difference in the loss of mass among the strongest and weakest groups of C20 PPDG concrete specimens and control group in compressive strength after 25, 50, 75 and 100 times of freeze-thaw cycle.

Number of freeze-thaw cycles	Variance source	Sum of squares	df	Root mean square	F	Significance
25	S_A	0.00	2	0.00	9.14	0.02
	S_E	0.00	6	0.00		
	S_T	0.00	8			
50	S_A	0.00	2	0.00	5.22	0.05
	S_E	0.00	6	0.00		
	S_T	0.00	8			
75	S_A	0.00	2	0.00	4.82	0.06
	S_E	0.00	6	0.00		
	S_T	0.00	8			

100	S_A	0.00	2	0.00 0.00	5.47	0.04

I: Difference in the loss of mass among the strongest and weakest groups of C30 PPDG concrete specimens and control group in compressive strength after 25, 50, 75 and 100 times of freeze-thaw cycle.

Number of freeze-thaw cycles	Variance source	Sum of squares	df	Root mean square	F	Significance
25	S_A	0.00	2	0.00 0.00	0.31	0.74
	S_E	0.00	6			
	S_T	0.00	8			
50	S_A	0.00	2	0.00 0.00	1.08	0.40
	S_E	0.00	6			
	S_T	0.00	8			
75	S_A	0.00	2	0.00 0.00	0.94	0.44
	S_E	0.00	6			
	S_T	0.00	8			
100	S_A	0.00	2	0.00 0.00	1.42	0.31
	S_E	0.00	6			
	S_T	0.00	8			

J: Difference in the loss of mass among the strongest and weakest groups of C40 PPDG concrete specimens and control group in compressive strength after 25, 50, 75 and 100 times of freeze-thaw cycle.

Number of freeze-thaw cycles	Variance source	Sum of squares	df	Root mean square	F	Significance
25	S_A	0.00	2	0.00 0.00	4.92	0.05
	S_E	0.00	6			
	S_T	0.00	8			
50	S_A	0.00	2	0.00 0.00	1.89	0.23
	S_E	0.00	6			
	S_T	0.00	8			
75	S_A	0.00	2	0.00 0.00	1.24	0.35
	S_E	0.00	6			
	S_T	0.00	8			
100	S_A	0.00	2	0.00 0.00	0.16	0.86
	S_E	0.00	6			
	S_T	0.00	8			

K: Difference in the compressive-strength between PPDG concretes before and after 100 freeze-thaw cycles. Each group included the strongest and weakest groups of C20, C30 and C40 concrete specimen (in which 1-30% cement was replaced by PPDG) and control group (in which no cement was replaced)

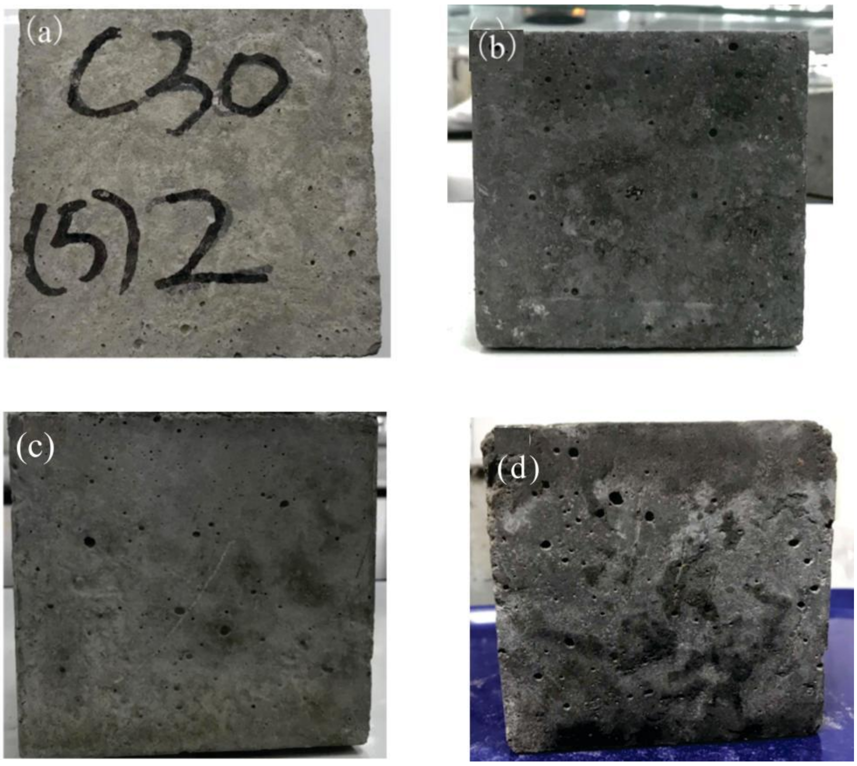
Variance source	Sum of squares	df	Root mean	F	Significance

			square		
S_A S_E S_T	178.788 2660.299 2839.087	1 52 53	178.788 51.160	3.495	0.067

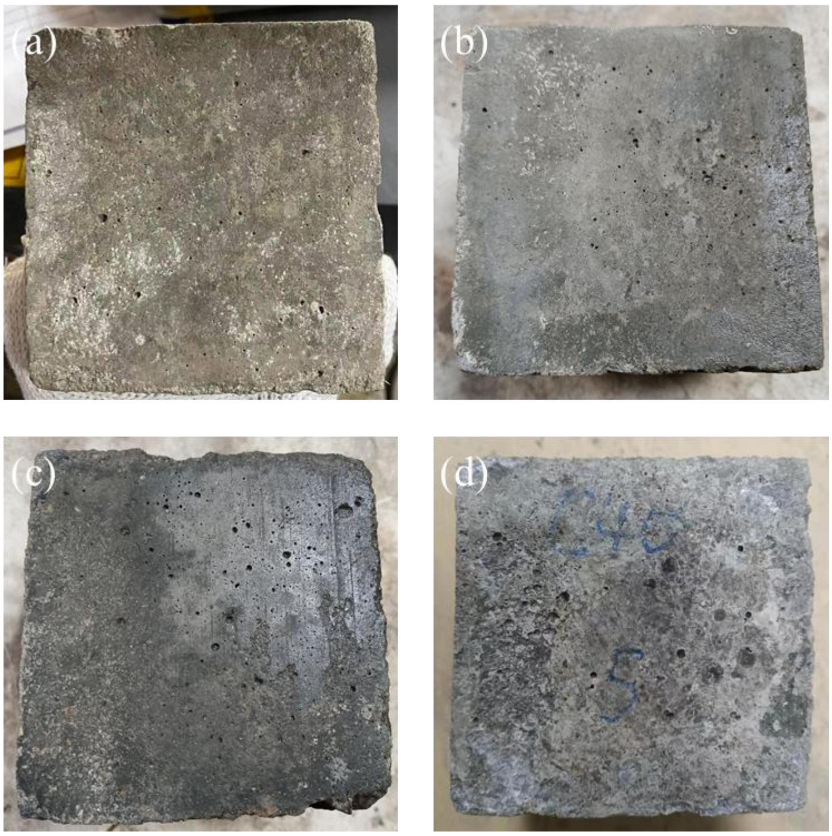
L Difference in the compressive strength among the strongest and weakest groups of PPDG concretes (in which 1-30% cement was replaced by PPDG) and their control group (in which no cement was replaced) before and after 100 freeze-thaw cycles

Freeze-thaw cycle	Concrete class	Variance source	Sum of squares	df	Root mean square	F	Significance
Before	C20	S_A	66.05	2	33.02	20.62	P = 0.00
		S_E	9.61	6	1.60		
		S_T	75.65	8			
	C30	S_A	4.99	2	2.50	0.44	P = 0.66
		S_E	34.19	6	5.70		
		S_T	39.18	8			
	C40	S_A	72.07	2	36.04	3.60	P =0.09
		S_E	60.06	6	10.01		
		S_T	132.13	8			
After	C20	S_A	39.26	2	19.63	3.08	P = 0.12
		S_E	38.26	6	6.38		
		S_T	77.52	8			
	C30	S_A	1.02	2	0.51	0.31	P = 0.74
		S_E	9.83	6	1.64		
		S_T	10.85	8			
	C40	S_A	23.74	2	11.87	2.50	P = 0.16
		S_E	28.44	6	4.74		
		S_T	52.18	8			

Supplementary file 3:



A: PPMS Concrete, C30(2) specimens, after 25(a), 50(b), 75(c) and 100 (d) freeze-thaw cycles



B: PPDG Concrete, C30(1), specimens after 25(a), 50(b), 75(c) and 100(d) freeze-thaw cycles

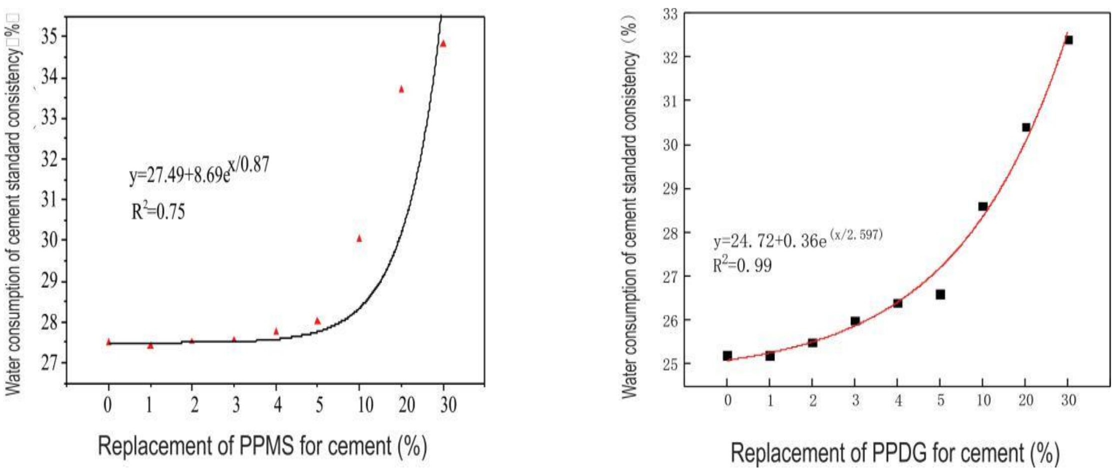
Supplementary file 4

Water consumption, setting time and fluidity

1 Water consumption for the standard consistency

As shown in Fig.1A, the replacement of the pyrolysis product of municipal sludge (PPMS) for cement increased the water consumption for cement standard consistency, and the higher the replacement proportion of PPMS, the more water consumption. When the replacement amount of PPMS was in the range of 1% - 3%, the water consumption for the cement standard consistency did not change significantly compared with control group. When the replacement amount increased to 5%, 10%, 20% and 30%, the water consumption of PPMS cement with these ratios rapidly increased by 1.86%, 9.25%, 22.60% and 26.64%, respectively, compared with control group.

The influence of the different replacement amount of the pyrolysis product of domestic garbage (PPDG) for cement on the water consumption for the cement standard consistency is shown in Fig. 1B. With the increase of PPDG substitution, the water consumption of the cement standard consistency increases gradually. The water consumption of control group for cement standard consistency was 25.2%. When the replacement amount of PPDG was in the range of less than 1%, the water consumption for the cement standard consistency did not change significantly compared with control group. However, when the substitution amount increased by more than 1%, the water consumption of cement standard consistency significantly increased compared with the control group. **Compared with PPMS containing a low content of carbon (8.7%), PPDG containing a high content of carbon (59.6%) significantly increased the water consumption for the cement standard consistency at the low ratio of the replacement for cement, indicating that carbon in cement could absorb more water to reach the cement standard consistency.**



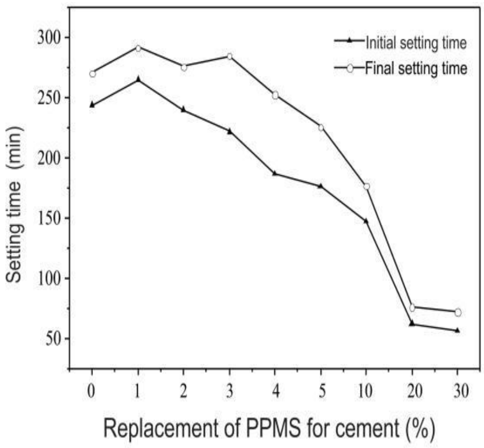
(a) (b)

Figure-1 Water consumption of PPMS (a) and PPDG (b) cement

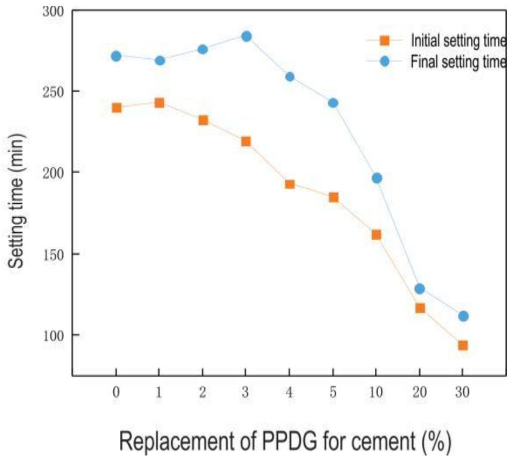
2 Setting time of PPMS and PPDG cement

As shown in Fig. 2A, the more the PPMS to replace cement, the shorter the initial and final setting time of PPMS cement. When the ratios of repalcement ranged less than 2% and 3%, the initial and final setting time of PPMS cement was similar to that of control group. When the ratios of the replacement for cement was more than 2% and 3%, the initial and final setting time of PPMS cement began to gradually shorten, especially when the ratios of replacement for cement was more than 10%, the initial setting time of PPMS cement decreased sharply. When the ratios of replacement was 20%, the PPMS cement initially set at 62 min, and when the the ratios of replacement was 30%, it initially set at 56 min. There was only 9 min different in the time.

The influence of PPDG substitution for cement on the initial and final setting time of cement is shown in Fig. 2B. When the replacement amount of PPDG was less than 2% and 3%, the initial and final setting time had no significant change compared with control group. The initial and final setting time of PPDG cement rapidly decreased with the increase of PPDG substitution when the substitution amount was more than 2% and 3%. When the substitution amount was 30%, the initial and final setting time of PPDG cement were shortened by 60.8% and 58.8% compared with control group. It was noted that when the replacement amount was 20% and 30%, the difference between the initial and final setting time was only 12 min and 18 min, respectively. **Comparatively, PPDG replacing cement needed more initial and final time of cement than PPMS at the same ratios of replacement, indicating that high carbon content resulted in long setting time.**



(b)



(b)

Figure-2 Setting time of PPMS (a) and PPDG (b) cement

3 Fluidity of PPMS and PPDG mortar

Fig. 3A shows the relationship between the replacement amount of PPMS and the fluidity of cement mortar. Generally speaking, the more PPMS replaced cement, the smaller the fluidity of PPMS cement mortar. When the replacement amount of PPMS was less than 2%, the fluidity of 325 and 425 cement mortar did not show obviously different compared with control group. When the replacement amount of PPMS was more than 2%, the fluidity of 325 and 425 cement mortar decreased gradually. Compared with control group, the fluidity of 325 cement mortar decreased by 20.47%, 43.62% and 50.39% respectively when the replacement amount was 10%, 20% and 30% and the fluidity of 425 cement mortar decreased by 18.66%, 46.27% and 46.27%, respectively. Similar to the water consumption for cement standard consistency, the higher the replacement proportion of PPMS, the more water absorbed to result in low fluidity. In order to control the same conditions of experiment, water was not supplemented to mortars during the test, so the cement mortar mixture become dry, loose and does not almost flow (30% replacement for cement, Fig. 3B).

Fig. 3C shows the effects of different PPDG substitution on the fluidity of 425 and 325 cement mortar, respectively. The fluidity of 425 cement mortar was higher than that of 325 mortar at any ratio of replacement. Compared with control group, the fluidity of PPDG mortar did not show obviously different at less than 2% replacement for cement. When the replacement amount of waste carbon was more than 2%, the fluidity gradually decreased, and the decrease range of the fluidity was small. When the substitution amount was 10%, 20% and 30%, the fluidity of 425 cement mortar decreased by 13.4%, 19.0% and 30.3%, respectively, and 325 mortars was by 11.1%, 15.7% and 30.0%, respectively. The mortar mixture was dry, hard, caked, rough and porous at 30% replacement.

The fluidity of 425 and 325 cement mortars with PPDG replacement for cement was higher than that with PPMS replacement for cement at any ratio of replacement, indicating that high-content carbon in PPMS and PPDG was relatively beneficial to the fluidity of mortars.

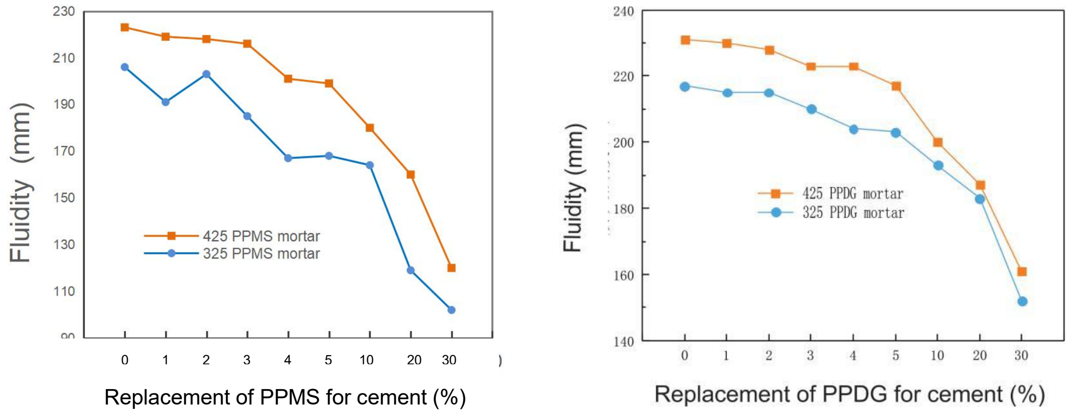
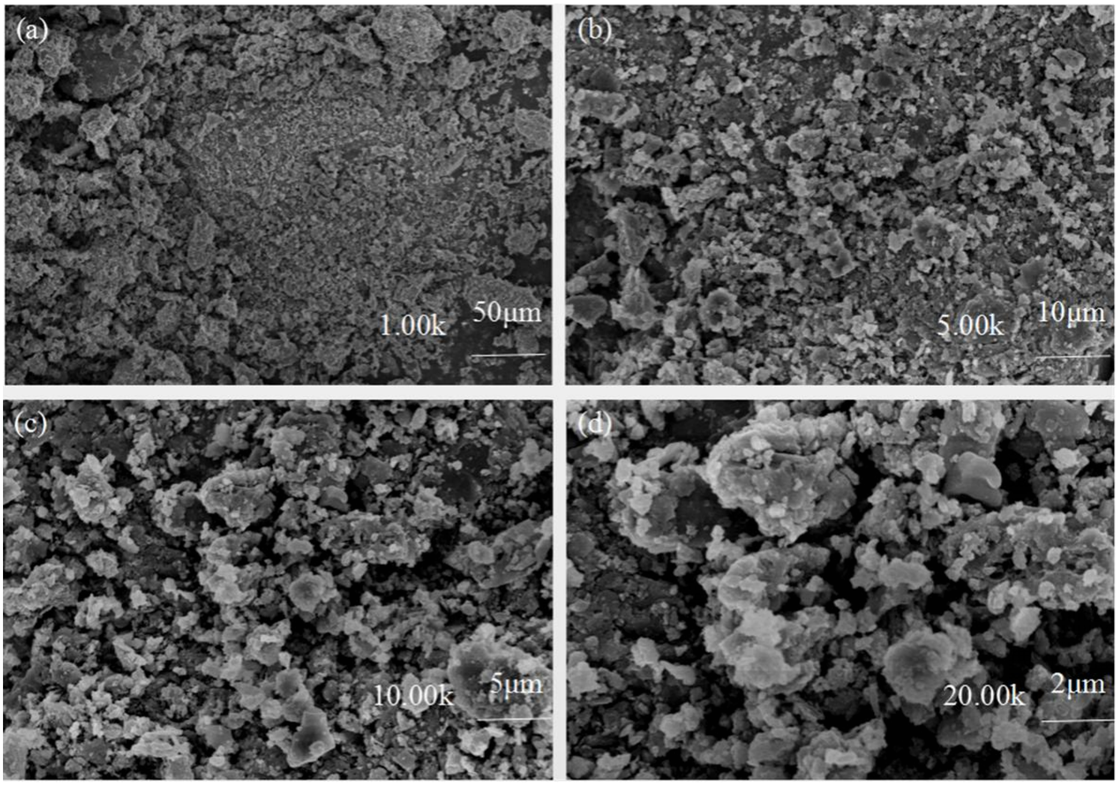
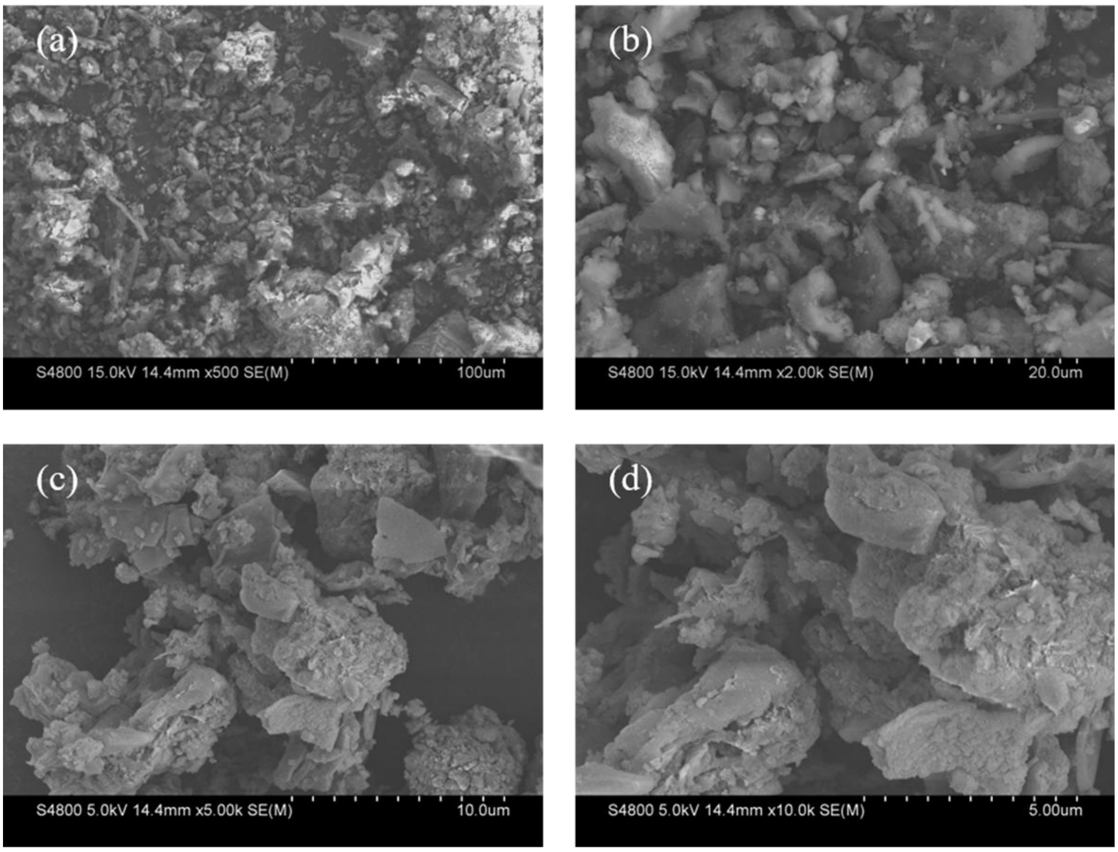


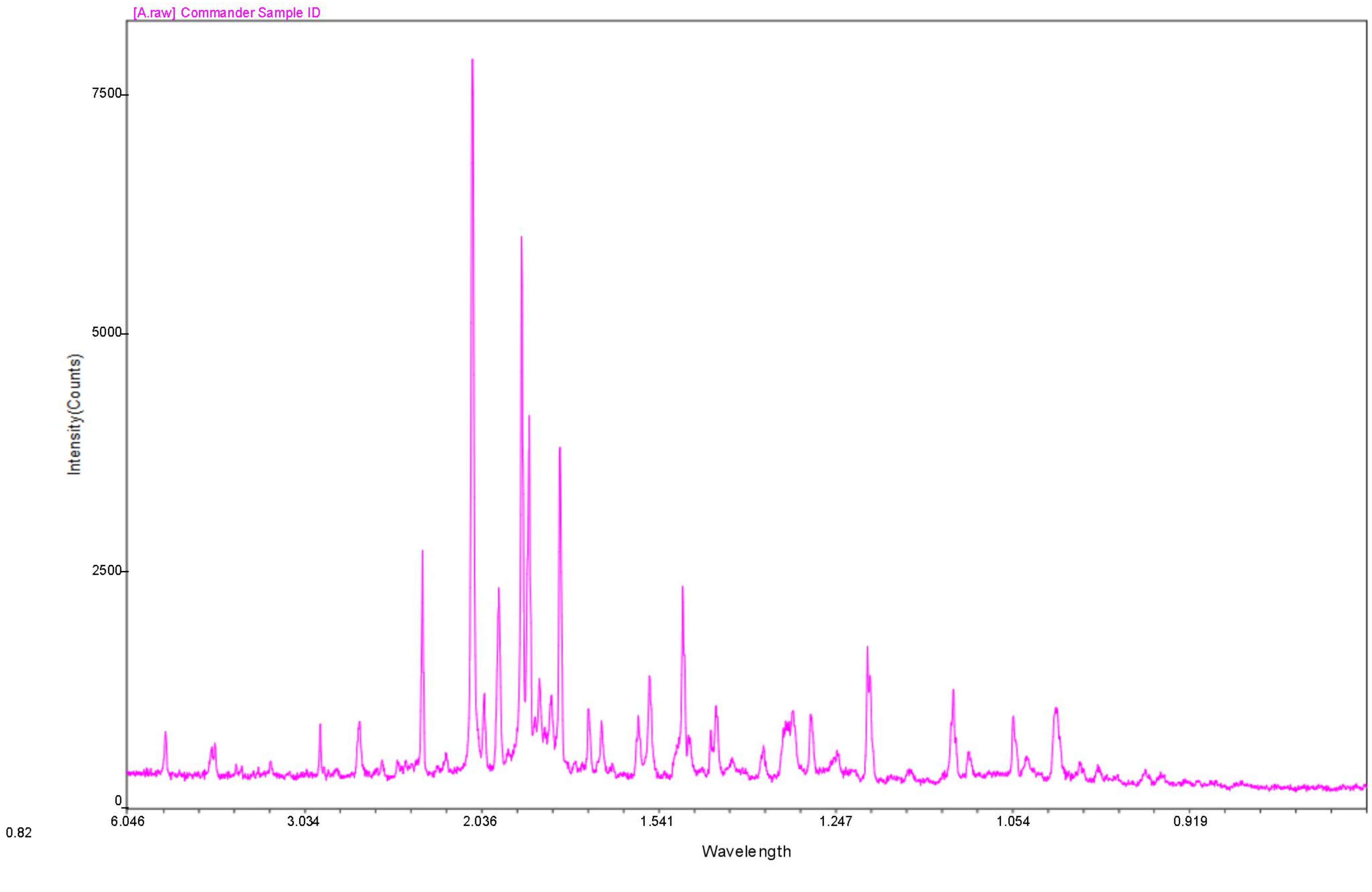
Figure-3 Fluidity of 425 and 325 cement mortars



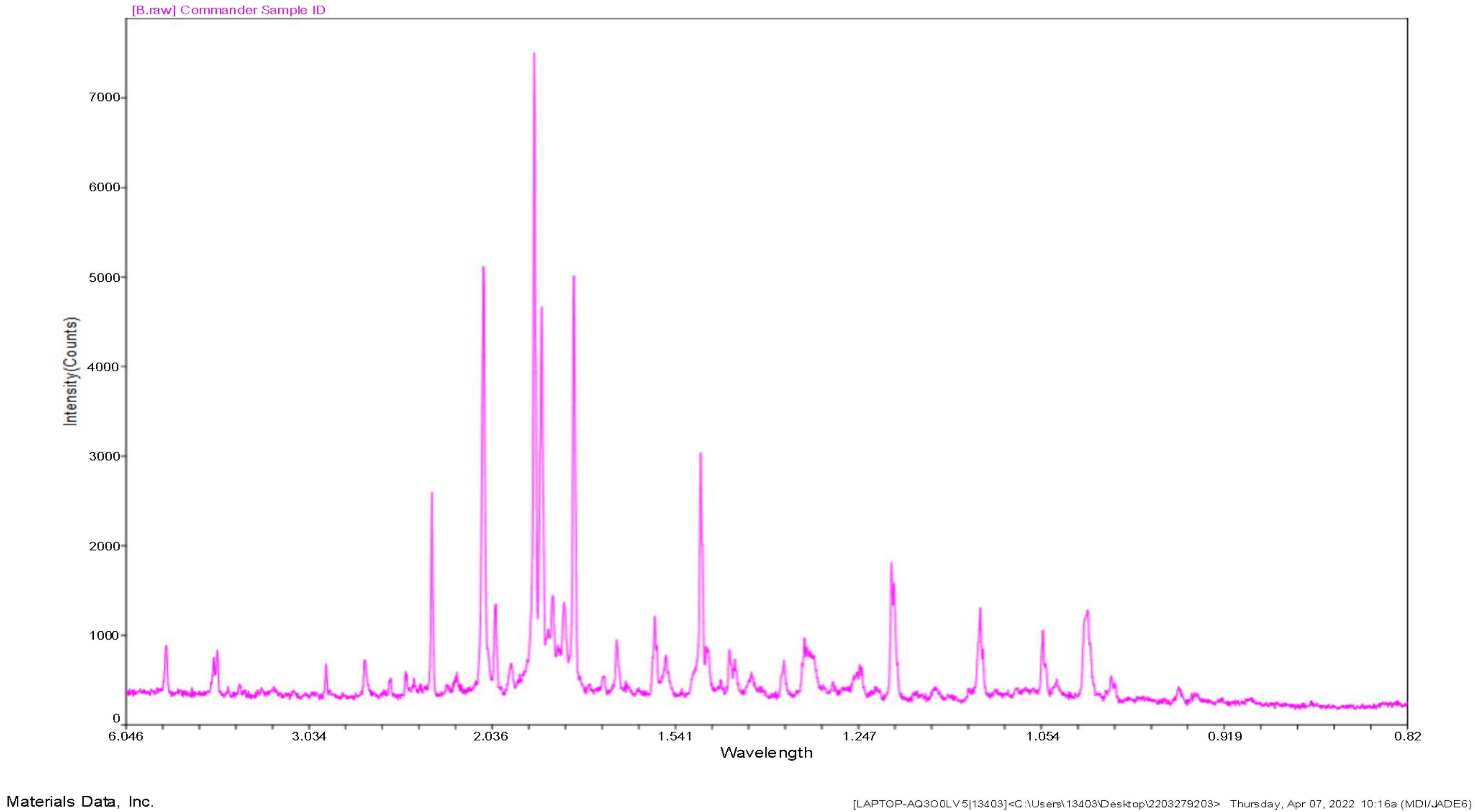
Supplementary file 5A SEM photos of the prysis product of municipal sludge (PPMS).（a）×1000（b）×5000;（c）×10000;（d）×20000



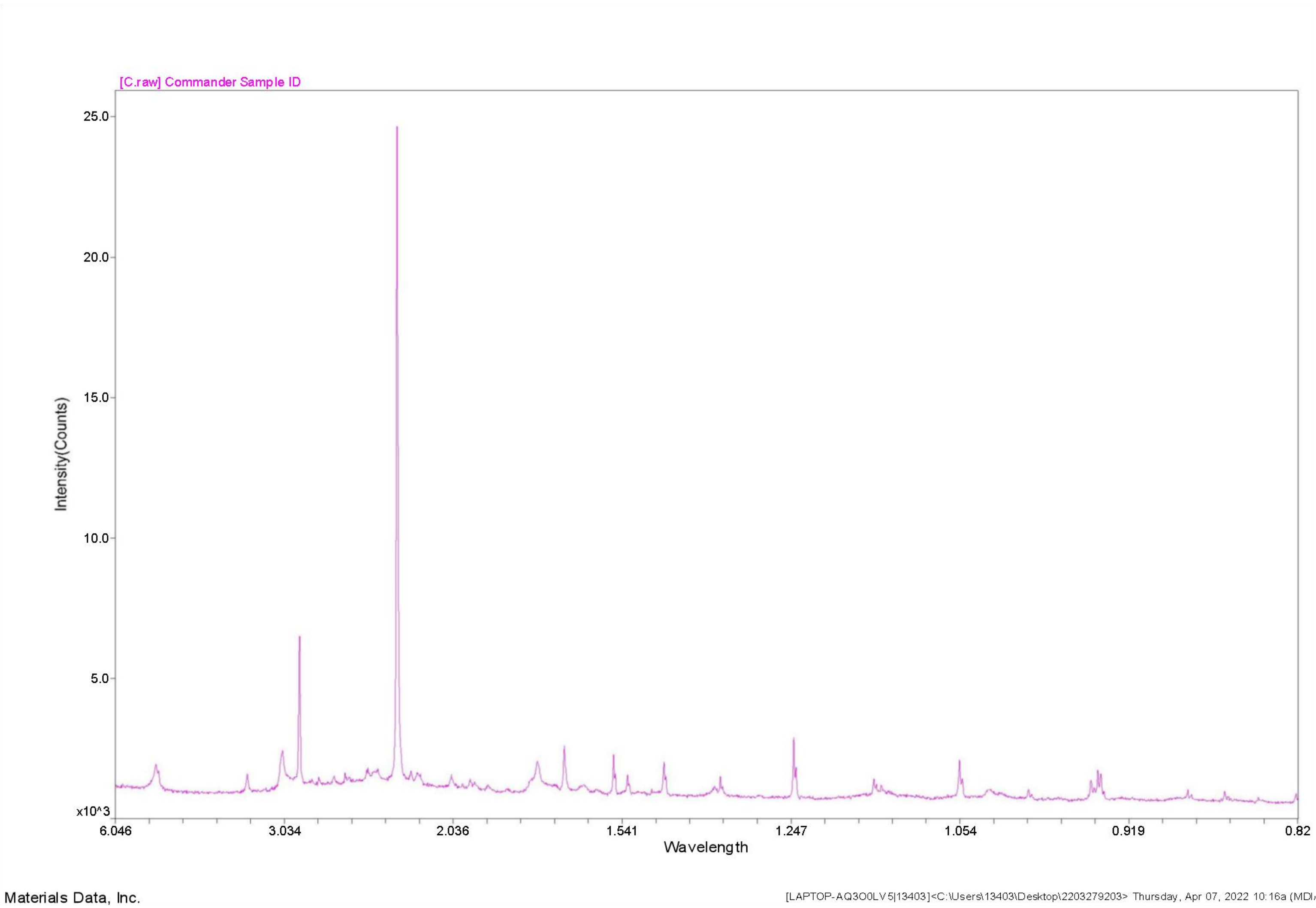
Supplementary file 5B SEM photos of PPDG.（a）×500;（b）×2000;（c）×5000;（d）×10000



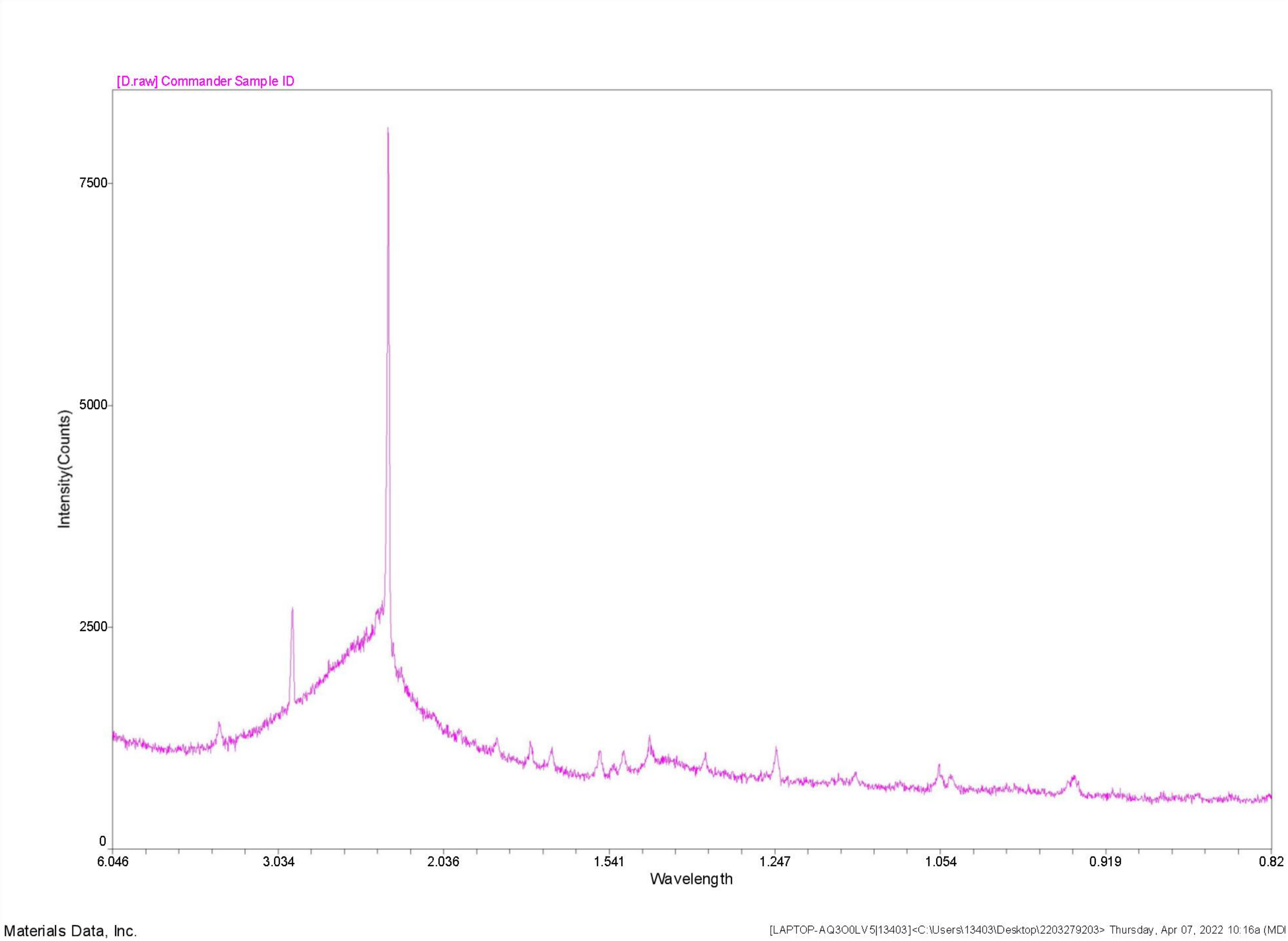
Supplementary file 6A XRD patterns of Portland 32.5 cement



Supplementary file 6B XRD patterns of Portland 42.5 cement



Supplementary file 3C XRD patterns of PPMS



Supplementary file 6D XRD patterns of PPDG

Supplementary file 7

Table A 5-10 mm stone single grain grading

Sieve number	Sieve residue (kg)	Sieve residue percentage (%)
16.0mm	0	0
13.2mm	0	0
9.50mm	0.154	10
4.75mm	1.310	95

Table B 10 mm-20 mm stone single grain grading

Sieve number	Sieve residue (kg)	Sieve residue percentage (%)
26.5mm	0	0
19.0mm	0.25	12.5
16.0mm	0.71	48.4
13.2mm	0.59	78.2
9.50mm	0.38	97.5

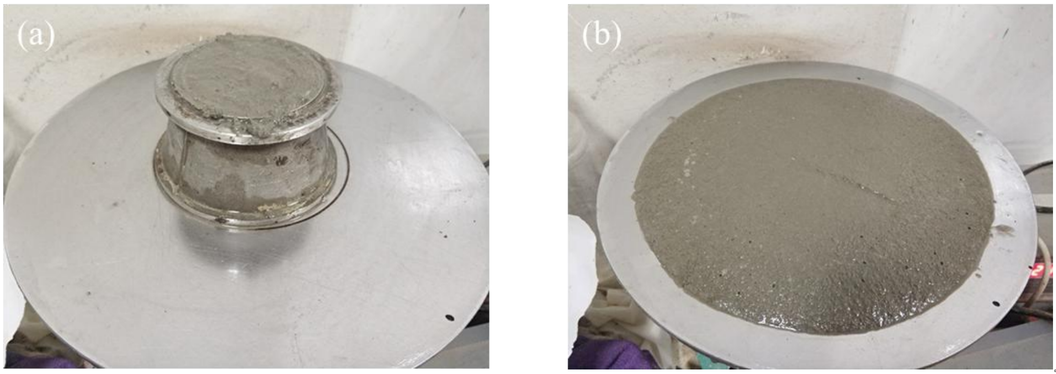
Table C 5 mm－20 mm stone single grain grading

Sieve number	Sieve residue (kg)	Sieve residue percentage (%)
26.5mm	0	0
19mm	0.39	7.69
16mm	1.22	31.92
9.5mm	1.91	70
4.75mm	1.38	97.6

Supplementary file 8

A: Hobart mixer

B: Wuxi Jianyi zs-15 cement mortar shaking table and cement mortar test block after shaking

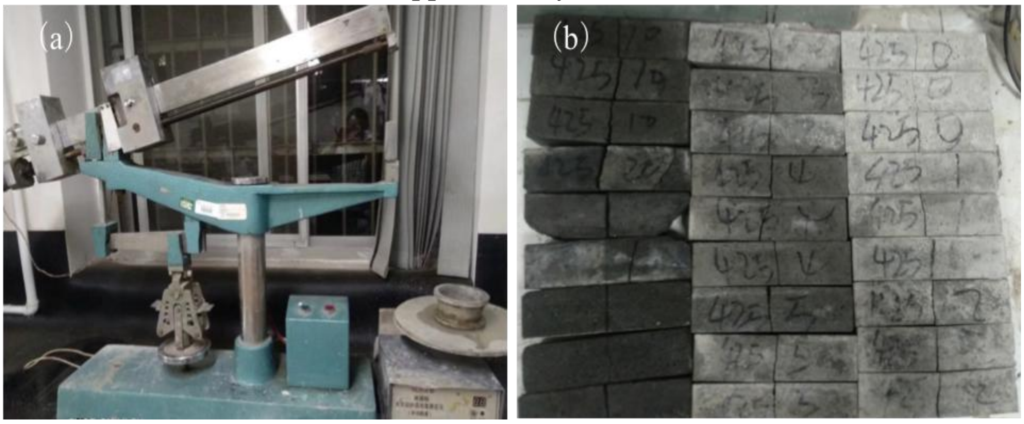


C: (a) Truncated cone circular die; (b) Table jumping to test fluidity

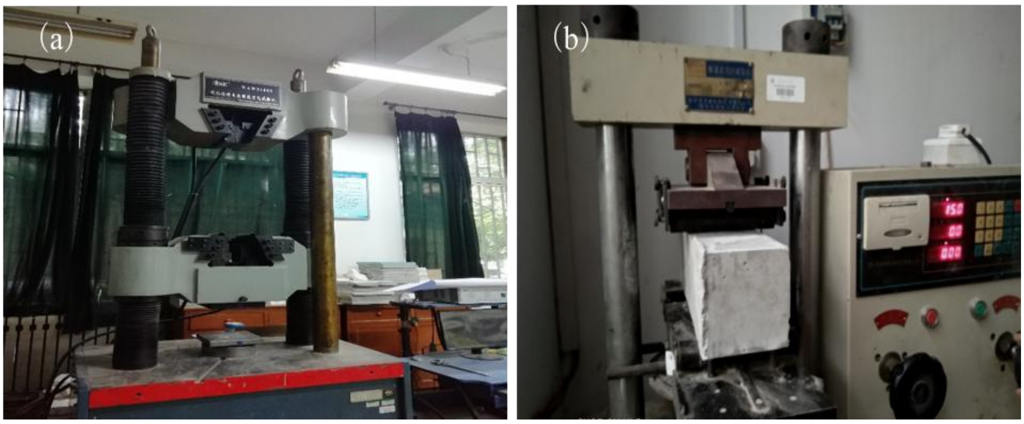
D: Concrete mixer

E: (a) Concrete shaking table (b) concrete test block without formwork removal

Supplementary file 9



A: (a) A fluxural strength tester of mortar specimens; (b) mortars after a test of fluxural strength



B: (a) Hydraulic electric servo universal press controlled by microcomputer; (b) YES-300B tester of press with digital display

C: Compressive failure mode for PPMS and PPDG concrete

D: Flexural failure mode for PPMS and PPDG concrete

E: Mode of splitting tensile failure for PPMS and PPDG concrete

Supplementary file 10

A: (a) Concrete freezing and thawing machine (b) concrete test block in frozen state

B: (a) Hitachi s-4800 cold field emission scanning electron microscope (b) xrd-6000 X-ray diffractometer