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Table 1 Phase analysis from the calculation of α-HH synthesized under various conditions.

P (bars)	T (°C)	t (min)	HH (%)		AIII (%)		AII (%)		DH (%)		Other (%)	
			FGD	NG	FGD	NG	FGD	NG	FGD	NG	FGD	NG
2	130	60	90.73±4.76	91.24±4.02	-	-	0.36±0.24	0.19±0.10	3.27±0.34	3.86±0.25	5.64±1.79	4.71±1.57
2	130	120	91.55±3.91	90.98±4.32	0.11±0.05	-	0.53±0.23	0.31±0.15	2.93±0.21	3.02±0.27	4.88±1.67	5.69±1.24
4	150	60	93.20±3.83	93.04±3.77	0.24±0.18	0.08±0.10	0.63±0.29	0.88±0.40	0.80±0.15	1.07±0.10	5.13±1.33	4.99±1.58
4	150	120	93.56±4.32	92.67±4.14	0.63±0.37	0.19±0.26	0.85±0.56	0.92±0.27	0.09±0.03	0.20±0.05	4.87±1.47	6.02±1.50
5	156	60	91.90±3.98	93.66±3.75	0.86±0.32	0.47±0.23	1.01±0.39	1.29±0.31	-	-	6.24±1.68	4.59±1.84
5	156	120	92.14±4.16	92.97±3.46	1.09±0.27	0.63±0.20	1.09±0..42	1.42±0.51	-	-	5.86±1.25	4.98±1.38
6	163	60	94.25±3.49	93.57±3.06	1.27±0.18	0.85±0.29	1.26±0.33	1.87±0.28	-	-	4.22±1.30	3.71±1.27
6	163	120	90.22±3.11	94.01±4.07	2.76±0.31	0.91±0.35	1.68±0.43	1.93±0.61	-	-	5.34±1.64	3.15±1.42
6	163	120	90.22±3.11	94.01±4.07	2.76±0.31	0.91±0.35	1.68±0.43	1.93±0.61	-	-	5.34±1.64	3.15±1.42
α-BSP			89.65±4.12		1.21±0.52		4.82±1.20		-		4.32±1.53	

P = pressure, T = temperature, and t = time

FGD = Flue gas gypsum briquettes, NG = Natural gypsum, α-BSP = Commercial product

Table 2 The suitable grinding conditions of synthetic α-HH (feeding size ≈ 2.0 mm 10#).

Additive	Dipping time (min)	Feeding rate (g/min)#	Median size (μm)			
			Lab autoclave		Production	
			FGD	NG	FGD	NG
α-HTGS			7.83±2.97			
-	-	15	-	7.76±0.35	-	7.65±0.26
		25	7.68±0.38	-	7.59±0.26	-
Sodium succinate	3	15	-	7.68±0.29	-	7.43±0.29
		25	7.59±0.97	-	7.60±0.32	-
	7	15	-	7.56±0.16	-	7.40±0.16
		30	7.79±0.42	-	7.81±0.31	-
	15	20	-	7.70±0.14	-	7.76±0.14
		30	7.47±0.76	-	7.60±0.26	-
Succinic acid	3	20	-	7.49±0.17	-	7.59±0.17
		30	7.56±0.81	-	7.51±0.31	-
	7	25	-	7.75±0.26	-	7.55±0.26
		35	7.68±0.42	-	7.48±0.26	-
	15	30	-	7.80±0.17	-	7.71±0.17
		40	7.87±0.81	-	7.77±0.19	-
Magnesium nitrate	3	15	-	7.73±0.20	-	7.49±0.20
		25	7.60±0.23	-	7.68±0.28	-
	7	15	-	7.48±0.17	-	7.62±0.17
		25	7.52±0.85	-	7.47±0.24	-
	15	20	-	7.71±0.20	-	7.60±0.20
		30	7.56±0.74	-	7.49±0.31	-
Mixture of Sodium Succinate and Magnesium nitrate (1:1)	3	15	-	7.90±0.27	-	7.74±0.52
		25	7.85±0.65	-	7.80±0.30	-
	7	15	-	7.53±0.44	-	7.65±0.70
		25	7.74±0.32	-	7.69±0.25	-
	15	20	-	7.69±0.19	-	7.57±0.38
		30	7.60±0.46	-	7.71±0.14	-

Lab grinding machine (FRITSCH Rotor Speed Mill Pulverisette 14), 15,000 rpm, 12 teeth, sieve = 1 mm.

Table 3 Phase analysis from the calculation of α-HH synthesized under various conditions.

Additive	Dipping time (min)	HH (%)		AIII (%)		AII (%)		DH (%)		Other (%)	
		FGD	NG	FGD	NG	FGD	NG	FGD	NG	FGD	NG
	α-HTGS	86.87±4.35		-		8.73±2.47		-		4.40±1.76	
-	-	93.03±3.40	93.21±3.76	1.32±0.26	1.06±0.34	1.39±0.41	1.64±0.24	-	-	3.26±1.46	4.09±1.82
Sodium succinate	3	94.49±3.86	93.52±3.20	< 0.01	< 0.01	0.83±0.21	0.47±0.67	-	-	4.68±1.42	6.01±1.64
	7	95.16±3.32	94.51±3.42	< 0.01	< 0.01	0.41±0.18	0.73±0.30	-	-	4.43±1.24	4.76±1.72
	15	95.20±3.93	95.37±3.93	< 0.01	< 0.01	0.52±0.22	0.90±0.28	-	-	4.28±1.40	3.73±1.61
Succinic acid	3	94.87±3.55	93.37±4.20	< 0.01	< 0.01	0.51±0.19	0.37±0.13	-	-	4.62±1.23	5.90±1.73
	7	96.02±3.84	94.80±3.24	< 0.01	< 0.01	0.26±0.20	0.39±0.20	-	-	3.72±1.45	4.81±1.67
	15	96.22±3.70	96.04±3.46	< 0.01	< 0.01	0.70±0.25	0.91±0.35	-	-	3.08±1.67	3.05±1.49
Magnesium nitrate	3	94.53±4.06	93.48±3.21	< 0.01	< 0.01	0.21±0.18	0.32±0.25	-	-	5.26±1.83	6.20±1.71
	7	95.02±3.51	94.23±3.96	< 0.01	< 0.01	0.33±0.11	0.57±0.23	-	-	4.65±1.53	5.20±1.34
	15	95.23±3.78	95.44±3.36	< 0.01	< 0.01	0.24±0.17	0.87±0.22	-	-	4.53±1.29	3.69±1.50
Mixture of Sodium succinate/ Magnesium nitrate (1:1)	3	94.76±4.11	93.64±3.50	< 0.01	< 0.01	0.36±0.11	0.47±0.12	-	-	4.88±1.72	5.89±1.35
	7	95.52±3.21	94.62±3.17	< 0.01	< 0.01	0.28±0.08	0.40±0.20	-	-	4.20±1.90	4.98±1.79
	15	95.87±3.60	95.70±3.46	< 0.01	< 0.01	0.42±0.19	0.31±0.15	-	-	3.71±1.59	3.99±1.61

FGD = Flue gas gypsum briquettes, NG = Natural gypsum, α-HTGS = Co mmercial product

Table 4 Physical and mechanical properties of α-HH synthesized under various conditions.

Additive	Dipping time (min)	pH→		Setting time (min)*				Flowability+ (cm)		Flexural strength# (MPa)	
				Initial		Final					
		FGD	NG	FGD	NG	FGD	NG	FGD	NG	FGD	NG
α-HTGS		11.1±0.10		18.52±0.87		35.50±1.50		23.50±0.05		12.67±0.89	
Sodium succinate 8.10±0.05	3	10.8±0.09	10.9±0.10	11.26±0.56	10.52±0.32	24.48±1.55	20.53±1.75	17.10±0.09	23.20±0.04	12.79±0.97	12.25±1.10
	7	10.9±0.07	10.9±0.07	12.25±0.84	12.43±0.71	22.20±1.64	22.42±1.56	17.00±0.06	23.05±0.10	13.53±1.36	13.03±1.43
	15	10.9±0.06	11.0±0.08	14.42±0.60	14.30±0.84	26.53±1.53	28.03±1.93	17.75±0.07	23.55±0.05	13.84±1.18	13.82±1.20
Succinic acid 1.90±0.10	3	10.0±0.05	10.6±0.06	14.57±0.52	13.48±0.47	29.20±1.70	24.39±1.66	16.30±0.10	22.95±0.09	13.06±1.31	12.85±0.68
	7	10.1±0.08	10.6±0.08	16.45±0.38	15.53±0.74	33.11±1.88	29.36±1.79	16.00±0.05	22.95±0.04	14.14±0.71	13.98±0.95
	15	10.2±0.10	10.7±0.08	17.36±0.42	17.50±0.68	32.10±1.55	33.50±2.04	16.00±0.05	22.90±0.06	14.36±0.75	14.60±1.18
Magnesium nitrate 7.00±0.05	3	10.8±0.06	10.9±0.04	7.16±0.80	7.46±0.52	12.30±1.63	15.24±1.63	17.30±0.08	23.50±0.11	12.90±0.79	12.19±0.82
	7	10.9±0.08	10.9±0.06	5.10±0.49	5.53±0.65	11.53±2.02	11.54±1.47	17.40±0.05	23.35±0.10	13.39±1.43	12.88±1.01
	15	11.0±0.05	11.0±0.07	4.20±0.78	4.47±0.70	9.37±1.69	9.47±1.94	17.25±0.07	23.20±0.09	13.57±1.57	13.71±1.15
Mixture of Sodium Succinate/Magnesium Nitrate (1:1)	3	10.8±0.05	10.9±0.10	10.05±0.32	9.16±0.62	21.53±1.45	18.23±1.54	17.00±0.06	23.30±0.07	13.01±1.42	12.62±0.91
	7	10.9±0.03	10.9±0.02	10.30±0.27	9.36±0.75	19.55±1.22	20.03±1.40	17.40±0.04	23.20±0.06	13.76±1.26	13.46±0.83
	15	11.0±0.06	11.0±0.05	10.57±0.48	10.04±0.29	21.17±1.38	19.40±1.43	17.30±0.05	23.00±0.03	14.00±0.78	14.02±1.38

FGD = F lue gas gypsum briquettes, NG = Natural gypsum, α-HTGS = Commercial product

* Condition of setting time testing - Room temperature 22°C, Water temperature 20°C, Humidity 71%, W/P = 0.37, + Larfarge method, # DIN 1168

Table 5 Amount of hemihydrate analyzed from both Infrared Moisture Determination Balance (IMDB) and Calculation.

Sample	Cycle	wt% HH (IMDB)*			wt% HH (Calculation)		
		FGD-T	FGD-G	NG	FGD-T	FGD-G	NG
Sodium succinate	1	98.50±0.48	99.20±0.53	98.20±3.41	96.01±3.75	97.11±4.02	95.27±3.41
(10 min)	2	98.20±1.75	98.90±0.38	98.00±3.53	95.71±3.42	96.85±3.99	95.01±3.53
	3	98.00±1.63	98.50±1.46	97.90±4.26	95.43±4.16	96.42±3.48	94.88±4.26
	4	97.70±1.48	98.20±1.75	97.70±3.47	94.87±4.05	96.38±3.55	94.51±3.47
	5	97.50±2.59	97.90±2.44	97.50±3.58	94.38±3.37	95.71±4.13	94.25±3.58
	6	97.20±3.15	97.50±1.13	97.20±3.45	94.14±3.88	95.42±3.79	93.83±3.45
	7	96.90±1.45	97.40±1.73	97.00±3.22	93.99±4.24	95.15±3.46	93.47±3.22
	8	96.70±2.35	97.20±2.26	96.80±4.11	93.40±3.53	95.07±3.36	93.31±4.11
Sodium succinate	1	99.40±0.21	99.90±0.28	99.00±3.12	96.24±3.70	97.11±4.02	95.98±3.12
(14 min)	2	98.90±0.47	99.50±0.59	98.50±3.89	95.90±3.21	96.85±3.58	95.76±3.89
	3	98.50±2.21	99.20±1.22	98.20±3.36	95.58±4.18	96.42±3.40	95.15±3.26
	4	97.80±1.27	98.50±1.03	97.80±3.74	95.15±3.39	96.38±4.14	94.72±3.74
	5	97.40±1.38	98.00±2.76	97.40±3.36	94.74±3.42	95.71±3.32	94.49±3.36
	6	97.20±2.00	97.80±1.95	97.20±3.75	94.17±4.00	95.42±3.47	94.02±3.75
	7	96.90±2.36	97.50±2.78	96.80±3.23	93.65±3.36	95.15±3.96	93.61±3.23
	8	96.20±2.27	97.40±2.26	96.30±4.18	93.19±4.27	95.07±3.58	93.32±4.18
Succinic acid	1	96.40±1.45	97.50±1.14	96.00±1.45	94.36±3.51	95.70±4.17	94.01±3.08
(3 min)	2	96.20±2.06	97.30±2.50	95.90±1.26	94.17±3.43	95.66±3.38	93.92±3.39
	3	96.00±1.55	97.10±2.24	95.70±2.14	94.02±3.68	95.58±3.46	93.84±3.75
	4	95.80±2.31	96.70±1.43	95.60±2.57	93.91±3.59	95.47±3.20	93.75±3.46
	5	95.50±1.65	96.50±2.24	95.50±2.47	93.80±3.87	95.39±3.81	93.63±3.85
	6	95.20±1.47	96.30±3.02	95.40±2.68	93.71±3.41	95.30±3.79	93.52±3.60
	7	95.10±2.04	96.20±2.65	95.30±2.38	93.53±4.20	95.25±3.35	93.47±3.30
	8	94.80±2.23	96.00±3.30	94.10±2.73	93.36±3.32	95.10±3.76	93.38±4.28
Succinic acid	1	97.50±2.20	98.00±1.70	97.10±1.70	95.21±3.54	96.77±4.31	94.58±3.7
(7 min)	2	97.10±1.30	97.80±1.34	96.70±2.30	95.06±3.33	96.48±4.25	94.30±3.46
	3	96.60±2.43	97.50±2.53	96.30±2.63	94.83±3.57	96.19±3.78	94.16±3.35
	4	96.20±2.24	97.20±2.14	96.10±2.65	94.44±4.23	96.01±3.50	94.02±4.12
	5	95.70±2.43	96.90±2.37	95.90±2.52	94.14±3.14	95.90±3.47	93.82±3.39
	6	95.30±3.11	96.70±3.21	95.50±2.47	93.65±4.09	95.78±3.39	93.75±3.47
	7	94.90±2.78	96.50±2.65	95.20±3.16	93.45±3.89	95.40±3.36	93.52±3.65
	8	94.30±2.54	96.20±2.45	94.90±2.55	93.22±3.36	95.12±3.45	93.44±3.34

*Infrared Moisture Determination Balance (A&D Company Limited AD 4713, AD4712)
FGD-T = Mae Moh flue gas gypsum briquettes, FGD-G = Lippendorf flue gas gypsum briquettes

Table 6 Phase analysis from the calculation of α-HH synthesized under various dipping cycles.

Sample	Cycle	HH (%)			AIII (%)			AII (%)			DH (%)			Other (%)		
		FGD-T	FGD-G	NG	FGD-T	FGD-G	NG	FGD-T	FGD-G	NG	FGD-T	FGD-G	NG	FGD-T	FGD-G	NG
α-HTGS		87.41±4.16			-			8.06±2.32			-			4.80±1.54		
Sodium succinate (10 min)	1	96.01±3.75	97.11±4.02	95.27±3.41	< 0.01	< 0.01	< 0.01	0.35±0.10	0.75±0.22	0.46±0.12	-	-	-	3.64±1.73	2.14±1.61	4.27±1.44
	2	95.71±3.42	96.85±3.99	95.01±3.53	< 0.01	< 0.01	< 0.01	0.46±0.26	0.35±0.10	0.75±0.21	-	-	-	3.83±1.56	2.80±1.46	4.24±1.30
	3	95.43±4.16	96.42±3.48	94.88±4.26	< 0.01	< 0.01	< 0.01	0.37±0.21	0.65±0.04	0.41±0.14	-	-	-	4.20±1.39	2.93±1.32	4.71±1.11
	4	94.87±4.05	96.38±3.55	94.51±3.47	< 0.01	< 0.01	< 0.01	0.66±0.17	0.41±0.26	0.74±0.26	-	-	-	4.47±1.46	3.21±1.28	4.75±1.64
	5	94.38±3.37	95.71±4.13	94.25±3.58	< 0.01	< 0.01	< 0.01	0.85±0.32	0.35±0.13	0.41±0.18	-	-	-	4.77±1.35	3.94±1.74	5.34±1.38
	6	94.14±3.88	95.42±3.79	93.83±3.45	< 0.01	< 0.01	< 0.01	0.44±0.08	0.80±0.14	0.59±0.23	-	-	-	5.42±1.40	3.78±1.21	5.58±1.76
	7	93.99±4.24	95.15±3.46	93.47±3.22	< 0.01	< 0.01	< 0.01	0.55±0.17	0.54±0.24	0.43±0.09	-	-	-	5.46±1.16	4.31±1.45	6.10±1.59
	8	93.40±3.53	95.07±3.36	93.31±4.11	< 0.01	< 0.01	< 0.01	0.90±0.35	0.43±0.15	0.76±0.36	-	-	-	5.70±1.93	4.50±1.36	5.53±1.42
Sodium succinate (14 min)	1	96.24±3.70	97.11±4.02	95.98±3.12	< 0.01	< 0.01	< 0.01	0.82±0.27	0.40±0.11	0.81±0.25	-	-	-	2.94±1.47	2.02±1.69	3.21±1.39
	2	95.90±3.21	96.85±3.58	95.76±3.89	< 0.01	< 0.01	< 0.01	0.50±0.09	0.61±0.20	0.32±0.17	-	-	-	3.60±1.50	2.28±1.27	3.92±1.03
	3	95.58±4.18	96.42±3.40	95.15±3.26	< 0.01	< 0.01	< 0.01	0.25±0.06	0.70±0.21	0.56±0.09	-	-	-	4.17±1.55	2.37±1.33	4.29±1.78
	4	95.15±3.39	96.38±4.14	94.72±3.74	< 0.01	< 0.01	< 0.01	0.70±0.21	0.58±0.09	0.36±0.22	-	-	-	4.15±1.42	2.77±1.51	4.92±1.46
	5	94.74±3.42	95.71±3.32	94.49±3.36	< 0.01	< 0.01	< 0.01	0.38±0.10	0.56±0.16	0.76±0.30	-	-	-	4.88±1.38	3.21±1.57	4.75±1.38
	6	94.17±4.00	95.42±3.47	94.02±3.75	< 0.01	< 0.01	< 0.01	0.63±0.15	0.21±0.04	0.66±0.16	-	-	-	5.20±1.90	4.00±1.48	5.32±1.45
	7	93.65±3.36	95.15±3.96	93.61±3.23	< 0.01	< 0.01	< 0.01	0.51±0.19	0.72±0.18	0.51±0.24	-	-	-	5.84±1.41	3.77±1.36	5.88±1.13
	8	93.19±4.27	95.07±3.58	93.32±4.18	< 0.01	< 0.01	< 0.01	0.76±0.21	0.32±0.09	0.85±0.28	-	-	-	6.05±1.73	4.48±1.45	5.83±1.99
Succinic acid (3 min)	1	94.36±3.51	95.70±4.17	94.01±3.08	< 0.01	< 0.01	< 0.01	0.70±0.17	0.31±0.16	0.46±0.18	-	-	-	4.94±1.85	3.99±1.55	5.33±1.95
	2	94.17±3.43	95.66±3.38	93.92±3.39	< 0.01	< 0.01	< 0.01	0.52±0.22	0.55±0.11	0.80±0.26	-	-	-	5.31±1.42	3.79±1.20	5.28±1.46
	3	94.02±3.68	95.58±3.46	93.84±3.75	< 0.01	< 0.01	< 0.01	0.47±0.04	0.51±0.14	0.60±0.12	-	-	-	5.51±1.60	3.91±1.99	5.56±1.63
	4	93.91±3.59	95.47±3.20	93.75±3.46	< 0.01	< 0.01	< 0.01	0.54±0.16	0.38±0.09	0.26±0.06	-	-	-	5.55±1.51	4.15±1.69	5.99±1.23
	5	93.80±3.87	95.39±3.81	93.63±3.85	< 0.01	< 0.01	< 0.01	0.38±0.13	0.76±0.30	0.30±0.09	-	-	-	5.82±1.98	3.15±1.73	6.07±1.58
	6	93.71±3.41	95.30±3.79	93.52±3.60	< 0.01	< 0.01	< 0.01	0.50±0.20	0.81±0.24	0.47±0.11	-	-	-	5.79±1.14	3.89±1.72	6.01±1.63
	7	93.53±4.20	95.25±3.35	93.47±3.30	< 0.01	< 0.01	< 0.01	0.81±0.25	0.63±0.16	0.42±0.14	-	-	-	5.66±1.42	3.82±1.35	6.11±1.17
	8	93.36±3.32	95.10±3.76	93.38±4.28	< 0.01	< 0.01	< 0.01	0.43±0.07	0.58±0.20	0.47±0.22	-	-	-	6.21±1.65	4.32±1.42	6.15±1.35
Succinic acid (7 min)	1	95.21±3.54	96.77±4.31	94.58±3.77	< 0.01	< 0.01	< 0.01	0.41±0.28	0.20±0.03	0.55±0.19	-	-	-	4.38±1.77	3.03±1.50	4.87±1.68
	2	95.06±3.33	96.48±4.25	94.30±3.46	< 0.01	< 0.01	< 0.01	0.63±0.30	0.70±0.23	0.76±0.17	-	-	-	4.31±1.11	2.82±1.58	5.40±1.52
	3	94.83±3.57	96.19±3.78	94.16±3.35	< 0.01	< 0.01	< 0.01	0.32±0.19	0.64±0.17	0.44±0.20	-	-	-	4.85±1.36	3.17±1.65	5.40±1.40
	4	94.44±4.23	96.01±3.50	94.02±4.12	< 0.01	< 0.01	< 0.01	0.21±0.11	0.54±0.20	0.76±0.19	-	-	-	5.35±1.45	3.36±1.44	5.22±1.22
	5	94.14±3.14	95.90±3.47	93.82±3.39	< 0.01	< 0.01	< 0.01	0.64±0.15	0.53±0.19	0.65±0.09	-	-	-	5.22±1.58	3.17±1.39	5.53±1.76
	6	93.65±4.09	95.78±3.39	93.75±3.47	< 0.01	< 0.01	< 0.01	0.39±0.06	0.43±0.11	0.53±0.18	-	-	-	5.96±1.78	3.79±1.26	5.72±1.11
	7	93.45±3.89	95.40±3.36	93.52±3.65	< 0.01	< 0.01	< 0.01	0.62±0.07	0.41±0.16	0.88±0.24	-	-	-	5.93±1.50	3.99±1.32	5.60±1.48
	8	93.22±3.36	95.12±3.45	93.44±3.34	< 0.01	< 0.01	< 0.01	0.45±0.12	0.26±0.04	0.85±0.17	-	-	-	6.33±1.66	4.62±1.74	5.71±1.88

FGD-T = Mae Moh flue gas gypsum briquettes, FGD-G = Lippendorf flue gas gypsum briquettes, NG = Natural gysum

Table 7 Physical and mechanical properties of α-HH synthesized under various dipping cycles.

Sample	Cycle	Setting time (min)*						Flowability+ (cm)			Flexural strength# (MPa)		
		Initial			Final								
		FGD-T	FGD-G	NG	FGD-T	FGD-G	NG	FGD-T	FGD-G	NG	FGD-T	FGD-G	NG
α-HTGS		17.13±0.59			33.45±2.13			23.50±0.05			12.75±0.95		
Sodium succinate (10 min)	1	13.50±0.56	13.22±0.48	13.09±0.22	27.36±1.75	27.15±2.04	27.25±1.64	17.10±0.02	21.50±0.02	23.20±0.08	13.55±1.18	13.76±1.32	13.15±1.28
	2	13.17±0.31	13.04±0.47	12.32±0.46	26.12±1.58	25.59±1.42	25.38±2.10	17.10±0.05	21.50±0.06	23.20±0.06	13.30±1.29	13.53±0.75	13.02±0.98
	3	12.20±0.45	12.35±0.59	11.50±0.37	25.37±1.34	23.49±1.58	25.04±1.63	17.05±0.06	21.50±0.04	23.20±0.05	13.16±1.36	13.26±0.99	12.94±1.16
	4	11.36±0.27	10.33±0.39	10.14±0.52	22.50±2.26	21.26±1.48	21.38±1.38	17.05±0.04	21.45±0.03	23.15±0.05	13.02±0.96	13.10±1.14	12.76±1.27
	5	10.47±0.36	9.53±0.38	9.26±0.49	21.12±1.49	19.14±1.81	20.35±1.75	17.05±0.05	21.40±0.01	23.15±0.02	12.87±1.03	12.93±1.19	12.63±0.86
	6	10.08±0.54	9.14±0.26	7.59±0.38	20.21±2.11	16.47±2.07	19.26±1.47	16.95±0.07	21.40±0.05	23.15±0.03	12.76±1.26	12.80±1.26	12.50±1.39
	7	9.32±0.16	8.46±0.58	7.36±0.17	18.02±1.49	15.50±1.40	17.11±1.63	16.95±0.06	21.40±0.06	23.10±0.04	12.60±0.88	12.69±1.27	12.39±1.15
	8	7.45±0.38	6.30±0.24	6.47±0.40	14.10±1.55	12.58±1.46	13.03±1.71	16.90±0.02	21.35±0.04	23.10±0.05	12.49±1.23	12.55±1.03	12.29±1.24
Sodium succinate (14 min)	1	14.56±0.56	14.34±0.29	14.29±0.50	29.47±1.93	29.35±1.67	29.16±1.42	17.60±0.03	21.80±0.03	23.55±0.02	13.69±1.35	13.90±0.76	13.65±1.27
	2	13.30±0.33	13.25±0.52	13.49±0.26	27.36±1.50	27.15±1.82	27.35±1.55	17.60±0.06	21.80±0.05	23.55±0.07	13.54±1.18	13.71±1.05	13.50±1.16
	3	12.07±0.56	11.59±0.46	13.11±0.42	25.35±1.86	25.12±2.17	26.46±1.76	17.55±0.02	21.75±0.06	23.50±0.04	13.31±1.01	13.52±1.18	13.25±1.25
	4	11.14±0.37	11.36±0.41	12.26±0.18	23.26±2.06	23.53±1.68	24.30±1.54	17.50±0.04	21.75±0.05	23.50±0.06	13.16±1.22	13.27±1.36	13.07±1.19
	5	10.46±0.54	10.24±0.39	11.47±0.29	21.25±2.21	20.38±1.64	22.11±1.38	17.50±0.04	21.70±0.03	23.50±0.05	13.00±0.96	13.11±1.20	12.96±1.09
	6	10.19±0.35	9.40±0.32	9.58±0.49	19.08±1.52	19.12±1.69	19.32±1.94	17.45±0.05	21.70±0.02	23.45±0.05	12.85±1.20	12.90±1.15	12.82±1.20
	7	8.43±0.16	7.52±0.33	9.14±0.39	17.11±2.11	16.59±1.71	18.04±1.75	17.45±0.03	21.70±0.04	23.45±0.02	12.67±1.09	12.76±0.93	12.53±0.89
	8	7.29±0.47	7.36±0.58	8.36±0.14	15.39±1.66	15.21±2.12	16.53±1.67	17.40±0.06	21.65±0.04	23.45±0.04	12.46±0.87	12.60±0.74	12.40±1.11
Succinic acid (3 min)	1	15.25±0.21	14.36±0.32	14.20±0.47	29.30±1.56	28.47±1.38	28.15±2.19	16.00±0.06	21.30±0.02	23.00±0.05	13.10±1.15	13.50±1.21	12.95±1.09
	2	14.13±0.48	13.20±0.56	13.46±0.17	28.43±1.73	28.03±1.69	27.65±1.53	16.00±0.05	21.30±0.04	23.00±0.02	13.01±1.23	13.35±1.14	12.81±0.91
	3	13.09±0.51	13.01±0.47	13.11±0.46	27.36±1.84	26.53±1.44	27.31±1.28	15.95±0.04	21.25±0.05	22.95±0.07	12.91±1.27	13.16±1.32	12.73±0.86
	4	12.39±0.63	12.41±0.50	13.00±0.38	26.31±2.11	25.38±1.75	26.46±1.36	15.95±0.03	21.25±0.05	22.95±0.04	12.76±1.22	13.00±1.01	12.60±1.35
	5	12.15±0.33	12.24±0.27	12.37±0.52	24.52±1.38	23.26±2.20	25.38±1.59	15.90±0.04	21.20±0.06	22.90±0.01	12.61±1.05	12.80±1.13	12.55±1.20
	6	12.00±0.24	11.47±0.56	12.11±0.40	24.44±1.76	24.11±1.42	24.36±2.10	15.90±0.02	21.20±0.04	22.90±0.03	12.53±0.98	12.72±1.25	12.41±1.18
	7	11.36±0.26	11.39±0.38	11.50±0.41	22.53±2.02	22.13±1.66	21.39±1.29	15.90±0.03	21.20±0.06	23.85±0.05	12.40±0.84	12.61±1.34	12.34±0.75
	8	10.46±0.49	10.27±0.57	11.18±0.39	20.39±1.93	19.57±1.58	23.57±1.77	15.85±0.05	21.15±0.07	23.85±0.02	12.31±1.30	12.48±1.07	12.26±1.03
Succinic acid (7 min)	1	17.00±0.56	16.45±0.37	16.10±0.31	35.26±1.76	34.47±1.93	35.02±1.32	15.95±0.06	21.10±0.02	22.95±0.03	14.01±1.31	14.38±1.17	13.94±1.06
	2	15.11±0.22	14.53±0.38	15.31±0.42	31.47±2.04	30.26±1.75	30.16±1.81	15.95±0.07	21.10±0.07	22.95±0.01	13.80±1.19	14.09±1.05	13.76±1.25
	3	13.26±0.52	13.14±0.39	14.22±0.46	28.47±1.58	27.59±2.14	29.46±1.65	15.90±0.05	21.05±0.06	22.90±0.05	13.65±1.02	13.80±1.23	13.53±1.10
	4	12.42±0.27	12.36±0.25	13.10±0.48	26.36±2.21	25.20±1.38	26.53±1.90	15.90±0.02	21.05±0.03	22.90±0.06	13.47±0.89	13.65±1.27	13.32±1.07
	5	11.35±0.54	11.21±0.36	11.46±0.59	24.01±1.93	23.36±1.49	24.43±1.88	15.85±0.06	21.00±0.04	22.90±0.04	13.30±1.19	13.47±1.06	13.16±0.91
	6	11.04±0.27	10.47±0.47	11.24±0.17	22.43±1.91	22.26±1.56	22.36±1.74	15.85±0.06	21.00±0.05	22.85±0.08	13.19±1.25	13.31±0.93	13.09±0.81
	7	10.37±0.53	10.10±0.59	10.35±0.35	20.59±1.80	21.10±2.19	21.43±2.07	15.80±0.03	19.95±0.05	22.85±0.05	13.01±1.06	13.17±1.26	12.92±1.11
	8	9.56±0.16	9.47±0.38	9.00±0.47	19.35±1.69	20.02±1.86	19.53±2.20	15.80±0.04	19.95±0.06	22.80±0.03	12.95±1.14	13.00±1.34	12.91±1.03

FGD-T = Mae Moh flue gas gypsu m briquettes, FGD-G = Lippendorf flue gas gypsum briquettes, NG = Natural gysum

* Condition of setting time testing - Room temperature 22°C, Water temperature 20°C, Humidity 71%, W/P = 0.37, + Larfarge method, # DIN 1168

Table 8 Effect of curing temperatures on the physical and mechanical properties of composite materials.

Properties	Curing temperature (°C)				
	20	40	50	65	80
Compressive strength (MPa)					
1 day	1.8	3.0	3.5	3.9	5.0
3 days	2.0	4.7	5.3	6.8	8.7
7 days	2.6	8.4	11.2	13.7	15.1
14 days	3.4	12.8	15.6	16.1	17.3
28 days	6.8	24.3	29.7	21.2	19.5
Bulk density (g/cm^3)					
1 day	1.18	1.20	1.21	1.20	1.22
3 days	1.19	1.25	1.26	1.27	1.29
7 days	1.19	1.31	1.35	1.36	1.37
14 days	1.21	1.45	1.45	1.47	1.48
28 days	1.28	1.56	1.68	1.53	1.50
Porosity (%)					
1 day	27.93	26.88	26.43	26.71	26.11
3 days	27.74	26.39	25.98	26.04	25.67
7 days	27.32	25.96	25.35	25.20	25.07
14 days	26.82	24.61	24.12	24.83	24.77
28 days	24.98	21.75	20.27	22.57	22.95
Volume change (%)					
1 day	-0.10	-0.12	-0.11	-0.09	-0.08
3 days	-0.15	-0.14	-0.17	-0.13	-0.12
7 days	-0.10	-0.09	-0.10	-0.08	-0.07
14 days	-0.06	-0.06	-0.02	-0.01	0.00
28 days	-0.03	0.03	0.06	0.02	0.01

Specimen : diameter = 50 mm, height = 50 mm.

Table 9 Effect of β-HH content on the physical and mechanical properties of composite materials.

Properties	Amount of β-HH (wt%)						
	0	30	40	50	60	70	100
Flowability (mm)	198	185	154	110	73	50	50
Compressive strength (MPa)							
1 day	0	1.8	2.8	3.5	5.2	6.6	9.0
3 days	0	2.0	4.1	5.4	6.1	8.3	11.3
7 days	1.1	2.6	5.0	7.6	9.5	10.4	12.6
14 days	2.0	3.4	7.3	8.7	10.8	11.7	14.0
28 days	3.2	6.8	10.7	11.8	12.6	13.5	16.5
Bulk density (g/cm^3)							
1 day	0	1.18	1.19	1.21	1.26	1.28	1.32
3 days	0	1.19	1.22	1.26	1.29	1.31	1.34
7 days	1.16	1.19	1.26	1.29	1.32	1.33	1.37
14 days	1.18	1.21	1.30	1.31	1.34	1.35	1.38
28 days	1.21	1.28	1.34	1.35	1.37	1.38	1.40
Porosity (%)							
1 day	0	27.93	27.62	26.66	25.75	25.06	24.75
3 days	0	27.74	26.41	25.70	25.25	24.80	24.40
7 days	28.87	27.32	25.88	25.10	24.80	24.70	24.25
14 days	27.95	26.82	24.90	24.77	24.62	24.52	23.95
28 days	27.10	24.98	24.51	24.39	24.23	24.07	23.47
Volume change (%)							
1 day	0	-0.10	-0.08	-0.06	-0.05	-0.03	0.00
3 days	0	-0.15	-0.12	-0.05	-0.02	0.01	0.02
7 days	-0.13	-0.10	-0.09	-0.01	0.01	0.04	0.06
14 days	-0.17	-0.06	-0.05	0.02	0.03	0.07	0.09
28 days	-0.14	-0.03	-0.02	0.04	0.07	0.09	0.15

Table 10 Performance of the mixtures of fly ash-lime and various amount of β-HH under water (20°C).

Immersion period (day)	Amount of β-HH (wt%)						
	0	30	40	50	60	70	100
Compressive strength (MPa)							
-	3.2	6.8	10.7	11.8	12.6	13.5	16.5
1 day	4.0	7.2	11.3	12.2	10.3	10.7	11.2
3 days	5.6	8.3	11.9	12.1	9.5	7.1	4 days*
7 days	7.8	9.5	12.5	11.1	6.4	7 days*	-
14 days	8.5	11.7	12.1	9.2	11 days*	-	-
28 days	10.5	13.2	11.9	18 days*	-	-	-
Water absorption (%)							
-	15.33	12.98	14.85	16.32	18.49	20.73	23.85
1 day	16.37	13.15	15.22	17.11	20.21	23.90	28.92
3 days	17.59	14.30	16.60	19.23	22.65	28.63	4 days*
7 days	19.63	14.89	18.89	21.56	26.40	7 days*	-
14 days	20.77	16.54	19.53	23.49	13 days*	-	-
28 days	21.44	18.47	22.21	24 days*	-	-	-
Volume change (%)							
-	-0.14	-0.03	-0.02	0.04	0.07	0.09	0.15
1 day	-0.13	-0.01	0.01	0.09	0.15	0.19	0.37
3 days	-0.10	0.01	0.03	0.12	0.21	0.33	4 days*
7 days	-0.06	0.05	0.08	0.17	0.38	7 days*	-
14 days	-0.01	0.08	0.11	0.24	13 days*	-	-
28 days	0.01	0.11	0.16	24 days*	-	-	-

Lea = Leaching

Table 11 Effect of additive on the physical and mechanical properties of composite materials cured at 20°C.

Properties	Non additive	$CaCl_2$ (wt%)				Na_2CO_3 (wt%)			
		1	2	3	4	1	2	3	4
Flowability (mm)	185	173	145	122	103	168	135	112	50
Compressive strength									
1 day	1.8	2.1	2.7	3.5	4.8	4.1	5.6	7.6	2.9
3 days	2.0	3.3	4.5	5.2	6.4	5.3	7.3	9.0	3.8
7 days	2.6	4.1	5.0	6.3	7.8	6.9	9.8	11.4	4.6
14 days	3.4	6.3	7.1	8.7	10.1	8.5	11.6	13.6	6.0
28 days	6.8	7.9	9.0	11.5	13.9	11.8	15.9	18.7	8.7
Bulk density (g/cm^3)									
1 day	1.18	1.20	1.21	1.21	1.27	1.24	1.26	1.30	1.20
3 days	1.19	1.21	1.24	1.26	1.29	1.26	1.30	1.34	1.21
7 days	1.19	1.24	1.27	1.29	1.31	1.29	1.32	1.36	1.25
14 days	1.21	1.28	1.30	1.32	1.35	1.32	1.35	1.39	1.29
28 days	1.28	1.32	1.34	1.36	1.39	1.36	1.41	1.46	1.32
Porosity (%)									
1 day	27.93	27.80	27.66	26.89	25.27	25.81	25.58	24.88	27.30
3 days	27.74	26.55	26.13	25.87	25.03	25.63	25.12	24.51	26.53
7 days	27.32	25.62	25.37	25.21	24.88	25.16	24.78	24.30	26.14
14 days	26.82	25.17	25.01	24.86	24.63	24.82	24.43	24.12	25.20
28 days	24.98	24.83	24.62	24.59	24.30	24.40	24.10	23.64	24.76
Volume change (%)									
1 day	-0.10	-0.07	-0.10	-0.09	-0.11	-0.14	-0.11	-0.13	-0.17
3 days	-0.15	-0.16	-0.18	-0.17	-0.19	-0.25	-0.20	-0.22	-0.24
7 days	-0.10	-0.14	-0.11	-0.13	-0.14	-0.20	-0.15	-0.16	-0.19
14 days	-0.06	-0.11	-0.08	-0.10	-0.09	-0.14	-0.10	-0.11	-0.16
28 days	-0.03	-0.07	-0.06	-0.05	-0.06	-0.10	-0.07	-0.04	-0.12

Table 12 Physical properties of mechanically accelerating composite materials cured at various ages.

Curing time	Properties			
	Compressive strength (MPa)	Bulk density (g/cm^3)	Porosity (%)	Volume change (%)
-	79.9	2.14	13.74	0
6 hours	80.3	2.14	13.73	0
12 hours	80.8	2.14	13.70	0
1 day	81.5	2.14	13.68	-0.011
3 days	85.8	2.15	13.45	-0.003
7 days	96.3	2.17	12.40	0.006
14 days	113.5	2.20	11.12	0.009
28 days	124.0	2.23	9.97	0.010

Table 13 Performance of 28-days mechanically accelerating composite materials under water (20°C).

Immersion period (day)	Properties		
	Compressive strength (MPa)	Water absorption (%)	Volume change (%)
-	124.0	1.93	0.002
1 day	126.5	2.89	0.009
3 days	128.2	3.17	0.03
7 days	133.4	3.65	0.07
14 days	137.0	3.82	0.09
28 days	142.1	5.69	0.15

Table 14 Effect of the thermally and chemically accelerating method on the physical and mechanical properties of composite materials.

Properties	Non additive Curing (°C)		$CaCl_2$ 4 wt% Curing (°C)		Na_2CO_3 3 wt% Curing (°C)	
	20	50	20	50	20	50
Compressive strength (MPa)						
1 day	1.8	3.5	5.3	11.7	7.7	14.7
3 days	2.0	5.3	7.7	15.5	9.5	23.1
7 days	2.6	11.2	10.1	21.4	12.2	33.6
14 days	3.4	15.6	11.6	27.7	14.3	41.2
28 days	6.8	27.1	15.2	37.1	19.5	43.5
60 days	9.3	34.2	19.9	45.7	24.6	44.3
90 days	12.5	38.8	25.6	50.6	29.3	45.2
Bulk density (g/cm^3)						
1 day	1.18	1.21	1.27	1.40	1.30	1.44
3 days	1.19	1.26	1.29	1.45	1.34	1.54
7 days	1.19	1.35	1.31	1.53	1.36	1.67
14 days	1.21	1.45	1.35	1.64	1.39	1.77
28 days	1.28	1.59	1.39	1.76	1.46	1.81
60 days	1.35	1.69	1.46	1.81	1.55	1.81
90 days	1.42	1.75	1.57	1.84	1.65	1.81
Porosity (%)						
1 day	27.93	26.43	25.27	24.11	24.80	23.74
3 days	27.74	25.98	25.03	23.15	24.51	21.37
7 days	27.32	25.35	24.88	22.04	24.30	17.94
14 days	26.82	24.12	24.63	20.33	24.12	15.71
28 days	24.98	20.27	24.30	17.09	23.64	14.74
60 days	24.63	18.95	22.11	14.65	20.36	14.70
90 days	24.01	16.80	20.17	13.09	18.65	14.65
Volume change (%)						
1 day	-0.10	-0.11	-0.11	-0.13	-0.13	-0.15
3 days	-0.15	-0.17	-0.19	-0.21	-0.22	-0.25
7 days	-0.10	-0.10	-0.14	-0.12	-0.16	-0.17
14 days	-0.06	-0.02	-0.09	-0.07	-0.11	-0.08
28 days	-0.05	0.06	-0.06	-0.01	-0.04	0.01
60 days	-0.03	0.07	-0.03	0.02	-0.01	0.03
90 days	-0.02	0.09	-0.01	0.05	0.01	0.03

Table 15. Effect of the thermally and chemically accelerating method on the performance under water of composite materials.

Immersion period (day)	Non additive Curing (°C)		$CaCl_2$ 4 wt% Curing (°C)		Na_2CO_3 3 wt% Curing (°C)	
	20	50	20	50	20	50
Compressive strength (MPa)						
-	6.8	29.7	13.9	36.7	18.7	43.5
1 day	7.2	30.5	14.2	37.2	19.1	44.3
3 days	8.3	32.6	16.3	39.9	21.6	44.9
7 days	9.5	39.5	20.5	43.6	24.5	46.3
14 days	11.7	43.6	25.4	46.0	32.9	48.0
28 days	13.2	48.0	30.6	52.4	37.0	49.5
60 days	17.1	50.3	34.6	54.6	41.5	49.7
90 days	21.0	52.6	39.2	55.0	45.6	49.8
Water absorption (%)						
-	12.98	6.15	8.86	4.57	7.89	3.10
1 day	13.15	8.16	9.20	5.22	8.76	3.36
3 days	14.30	8.47	9.76	5.70	9.23	3.75
7 days	14.89	9.29	10.53	6.33	9.69	4.69
14 days	16.54	9.50	11.69	6.78	10.48	5.26
28 days	18.47	11.44	14.01	8.12	12.20	7.19
60 days	19.56	12.57	16.16	8.40	14.73	7.20
90 days	20.73	13.24	18.03	8.58	16.21	7.21
Volume change (%)						
-	-0.03	0.06	-0.06	0.00	-0.04	0.01
1 day	-0.01	0.15	-0.03	0.04	-0.03	0.03
3 days	0.01	0.19	0.01	0.10	-0.02	0.07
7 days	0.05	0.24	0.03	0.14	0.01	0.11
14 days	0.08	0.33	0.06	0.19	0.04	0.15
28 days	0.14	0.38	0.09	0.21	0.06	0.18
60 days	0.50	0.45	0.30	0.24	0.34	0.18
90 days	0.80	0.49	0.60	0.26	0.68	0.18

Table 16. Effect of wetting/drying cyclic storage on the physical and mechanical properties of composite materials activated by thermally and chemically accelerating method.

Properties	Non-additive Curing (°C)		$CaCl_2$ 4 wt% Curing (°C)		Na_2CO_3 3 wt% Curing (°C)	
	20	50	20	50	20	50
Compressive strength (MPa)						
-	6.8	29.7	15.2	37.1	19.5	43.5
10 cycles	6.3	29.1	14.4	36.8	19.1	43.3
20 cycles	5.5	28.5	14.1	36.3	18.3	42.8
30 cycles	4.9	27.6	13.1	35.8	17.2	42.4
50 cycles	4.3	25.5	12.4	34.4	16.0	41.1
100 cycles						
Bulk density (g/cm^3)						
-	1.28	1.68	1.39	1.76	1.46	1.81
10 cycles	1.28	1.68	1.39	1.75	1.46	1.81
20 cycles	1.27	1.67	1.38	1.75	1.45	1.80
30 cycles	1.26	1.66	1.37	1.74	1.44	1.80
50 cycles	1.25	1.65	1.36	1.74	1.44	1.79
100 cycles						
Linear change (%)						
-	0	0	0	0	0	0
10 cycles	0.11	0.04	0.05	0.03	0.07	0.01
20 cycles	0.25	0.11	0.17	0.08	0.14	0.05
30 cycles	0.41	0.22	0.32	0.12	0.26	0.07
50 cycles	0.70	0.34	0.48	0.17	0.42	0.11
100 cycles						

Table 17. Effect of the combination of 3 accelerating methods on the physical and mechanical properties of composite materials.

Properties	Non additive Curing (°C)		$CaCl_2$ 4 wt% Curing (°C)		Na_2CO_3 3 wt% Curing (°C)	
	20	50	20	50	20	50
Compressive strength (MPa)						
1 day	80.7	81.5	81.6	83.7	82.0	83.9
3 days	83.6	85.8	85.1	91.2	85.9	96.9
7 days	87.5	96.3	92.7	103.6	94.6	114.8
14 days	92.3	113.5	105.8	124.7	110.8	131.6
28 days	98.6	124.0	115.9	143.8	120.3	152.3
60 days	100.9	128.8	118.5	146.8	123.6	154.4
90 days	10.42	132.2	121.3	149.5	127.4	154.5
Bulk density (g/cm^3)						
1 day	2.14	2.14	2.14	2.15	2.14	2.15
3 days	2.15	2.15	2.15	2.16	2.15	2.17
7 days	2.15	2.17	2.16	2.19	2.16	2.20
14 days	2.16	2.20	2.17	2.23	2.18	2.25
28 days	2.17	2.23	2.20	2.27	2.21	2.29
60 days	2.17	2.23	2.20	2.28	2.22	2.29
90 days	2.17	2.24	2.21	2.28	2.23	2.29
Porosity (%)						
1 day	13.76	13.68	13.61	13.60	13.53	13.55
3 days	13.62	13.45	13.55	12.93	13.41	12.20
7 days	13.26	12.40	12.91	11.97	12.70	11.03
14 days	12.83	11.12	11.82	9.92	11.43	9.35
28 days	12.15	9.78	10.61	8.89	11.90	8.21
60 days	11.95	9.62	10.35	8.75	9.98	8.21
90 days	11.79	9.49	10.16	8.53	9.82	8.20
Volume change (%)						
1 day	-0.014	-0.002	-0.010	0.005	-0.008	0.010
3 days	-0.010	0.002	-0.006	0.007	-0.002	0.012
7 days	-0.005	0.006	-0.002	0.010	-0.001	0.015
14 days	0.001	0.009	0.001	0.014	0.004	0.020
28 days	0.003	0.015	0.007	0.019	0.001	0.022
60 days	0.005	0.016	0.009	0.020	0.012	0.022
90 days	0.008	0.018	0.010	0.024	0.013	0.022

Table 18. Effect of the combination of 3 accelerating methods on the performance under water of the 28-day composite materials.

Properties	Non additive Curing (°C)		$CaCl_2$ 4 wt% Curing (°C)		Na_2CO_3 3 wt% Curing (°C)	
	20	50	20	50	20	50
Compressive strength (MPa)						
-	98.6	124.0	117.9	143.8	120.3	152.3
1 day	99.7	127.6	118.5	143.9	122.9	152.3
3 days	101.5	128.2	120.1	144.0	125.3	152.4
7 days	104.7	130.7	123.6	144.4	128.7	152.9
14 days	108.3	137.0	126.1	144.8	131.7	153.5
28 days	113.6	138.5	128.9	145.9	133.8	154.6
60 days	115.2	139.2	129.6	145.5	135.1	153.9
90 days	118.1	140.1	131.5	145.9	136.9	154.2
Water absorption (%)						
-	2.75	1.92	2.46	1.52	2.21	1.38
1 day	3.12	2.10	2.76	1.68	2.51	1.40
3 days	3.56	2.36	3.20	1.73	2.83	1.38
7 days	4.38	2.67	3.73	1.76	3.34	1.39
14 days	4.75	2.77	4.12	1.76	3.65	1.39
28 days	5.50	2.83	4.62	1.79	4.17	1.40
60 days	5.73	2.95	4.70	1.80	4.22	1.40
90 days	5.91	3.06	4.81	1.80	4.31	1.40
Volume change (%)						
-	0.003	0.046	0.007	0.03	0.01	0.018
1 day	0.016	0.053	0.03	0.04	0.04	0.024
3 days	0.096	0.06	0.08	0.05	0.07	0.031
7 days	0.12	0.07	0.10	0.06	0.09	0.038
14 days	0.15	0.09	0.12	0.06	0.11	0.044
28 days	0.16	0.10	0.14	0.07	0.13	0.048
60 days	0.17	0.11	0.15	0.07	0.14	0.05
90 days	0.18	0.12	0.16	0.08	0.14	0.05

Table 19. Effect of wetting/drying cyclic storage on the physical and mechanical properties of composite materials activated by the combination of 3 accelerating methods.

Properties	Non additive Curing (°C)		$CaCl_2$ 4 wt% Curing (°C)		Na_2CO_3 3 wt% Curing (°C)	
	20	50	20	50	20	50
Compressive strength (MPa)						
-	98.6	124.0	115.9	143.8	120.3	152.3
10 cycles	98.0	123.8	115.6	143.7	120.1	152.2
20 cycles	97.5	123.5	115.0	143.5	119.5	152.0
30 cycles	97.2	123.2	114.5	143.2	119.1	151.8
50 cycles	96.2	122.1	113.9	143.0	118.3	151.6
100 cycles	94.0	120.3	111.7	143.0	115.9	151.3
Bulk density (g/cm^3)						
-	2.17	2.23	2.20	2.27	2.21	2.29
10 cycles	2.17	2.23	2.20	2.27	2.21	2.29
20 cycles	2.16	2.22	2.19	2.27	2.21	2.28
30 cycles	2.16	2.22	2.19	2.26	2.20	2.28
50 cycles	2.15	2.21	2.18	2.26	2.19	2.28
100 cycles	2.13	2.20	2.17	2.26	2.18	2.28
Linear change (%)						
-	0	0	0	0	0	0
10 cycles	0	0	0	0	0	0
20 cycles	0.006	0.001	0.003	0	0.002	0
30 cycles	0.009	0.003	0.006	0.0006	0.004	0
50 cycles	0.01	0.005	0.008	0.0010	0.006	0.0003
100 cycles	0.01	0.006	0.009	0.0015	0.007	0.0007

Table 20. Effect of lime mud and sludge waste content on the physical and mechanical properties of lime-containing composite materials cured at 20°C.

Properties	Standard	Amount of lime mud (wt%)					Amount of sludge waste (wt%)				
		10	30	50	70	100	10	30	50	70	100
Flowability (mm)	186	186	184	185	185	186	167	143	96	50	50
Compressive strength											
1 day	1.8	1.7	1.5	1.2	0.9	0.6	1.6	1.4	1.0	0.6	0.3
3 days	2.0	1.9	1.8	1.5	1.2	0.9	1.9	1.7	1.3	1.0	0.7
7 days	2.6	2.4	2.2	2.0	1.7	1.4	2.3	2.1	1.9	1.5	1.1
14 days	3.4	3.1	3.0	2.8	2.2	1.9	3.2	2.9	2.5	2.1	1.8
28 days	6.8	6.6	6.4	6.1	4.9	3.8	6.5	6.2	5.1	4.5	3.5
Bulk density (g/cm^3)											
1 day	1.18	1.18	1.17	1.16	1.15	1.15	1.18	1.17	1.16	1.15	1.14
3 days	1.19	1.18	1.18	1.16	1.16	1.16	1.19	1.18	1.16	1.16	1.15
7 days	1.19	1.19	1.18	1.18	1.17	1.17	1.20	1.19	1.18	1.17	1.16
14 days	1.21	1.20	1.20	1.19	1.19	1.18	1.21	1.20	1.19	1.19	1.18
28 days	1.26	1.25	1.24	1.23	1.21	1.20	1.25	1.24	1.22	1.20	1.19
Porosity (%)											
1 day	27.93	28.35	28.92	29.46	30.70	31.68	28.51	29.42	31.21	32.33	33.68
3 days	27.74	28.04	28.50	28.92	29.92	30.66	28.07	28.83	30.41	31.52	32.45
7 days	27.32	27.45	27.80	28.23	28.90	29.55	27.66	28.26	29.06	30.02	30.98
14 days	26.82	27.00	27.29	27.60	28.06	28.48	27.04	27.43	27.80	28.51	29.08
28 days	24.98	25.34	25.70	26.05	26.97	27.52	25.28	25.76	26.29	27.07	27.62
Volume change (%)											
1 day	-0.10	-0.10	-0.09	-0.12	-0.13	-0.12	-0.10	-0.11	-0.09	-0.07	-0.08
3 days	-0.15	-0.14	-0.13	-0.14	-0.16	-0.17	-0.13	-0.11	-0.09	-0.07	-0.08
7 days	-0.10	-0.11	-0.12	-0.16	-0.18	-0.11	-0.11	-0.09	-0.09	-0.08	-0.09
14 days	-0.06	-0.07	-0.08	-0.10	-0.14	-0.07	-0.07	-0.07	-0.08	-0.08	-0.09
28 days	-0.03	-0.05	-0.05	-0.06	-0.09	-0.10	-0.05	-0.06	-0.07	-0.08	-0.09

Table 21. Effect of the thermally and chemically accelerating method on the physical and mechanical properties of lime-containing composite materials.

Properties	Lime mud 50 wt%			Sludge waste 30 wt%		
	Non additive	$CaCl_2$ 4 wt%	Na_2CO_3 3 wt%	Non additive	$CaCl_2$ 4 wt%	Na_2CO_3 3 wt%
Compressive strength (MPa)						
1 day	6.4	8.7	10.6	8.2	11.3	13.8
3 days	8.6	12.3	15.5	11.0	16.2	20.7
7 days	11.8	19.7	22.3	15.0	23.3	19.0
14 days	15.1	26.5	31.7	19.1	30.8	35.4
28 days	19.4	29.6	34.6	23.0	33.5	37.6
60 days	22.5	33.6	35.2	24.2	36.9	38.5
90 days	25.7	37.8	35.5	26.8	40.6	38.8
Bulk density (g/cm^3)						
1 day	1.27	1.32	1.35	1.30	1.34	1.36
3 days	1.32	1.36	1.41	1.35	1.39	1.45
7 days	1.37	1.46	1.54	1.39	1.53	1.61
14 days	1.42	1.60	1.66	1.45	1.65	1.69
28 days	1.46	1.63	1.68	1.50	1.70	1.75
60 days	1.49	1.66	1.68	1.53	1.74	1.76
90 days	1.51	1.70	1.68	1.56	1.79	1.76
Porosity (%)						
1 day	26.05	24.63	24.18	25.80	24.60	23.68
3 days	26.25	24.20	23.52	25.02	23.62	22.64
7 days	24.04	23.20	21.98	23.91	22.05	21.12
14 days	23.60	21.53	20.45	23.07	20.12	19.20
28 days	22.67	20.20	19.46	21.86	18.54	17.11
60 days	22.33	19.55	19.32	21.38	17.35	17.02
90 days	21.78	18.63	19.28	20.38	16.47	17.00
Volume change (%)						
1 day	-0.11	-0.12	-0.11	-0.06	-0.07	-0.01
3 days	-0.15	-0.16	-0.18	-0.04	-0.01	0.00
7 days	-0.10	-0.09	-0.12	0.01	0.02	0.01
14 days	-0.01	-0.05	-0.04	0.05	0.03	0.01
28 days	0.02	-0.01	0.00	0.05	0.03	0.01
60 days	0.05	0.01	0.02	0.06	0.04	0.02
90 days	0.08	0.05	0.03	0.07	0.04	0.02

Table 22. Effect of the thermally and chemically accelerating method on the performance under water of lime-containing composite materials.

Properties	Lime mud 50 wt%			Sludge waste 30 wt%		
	Non additive	$CaCl_2$ 4 wt%	Na_2CO_3 3 wt%	Non additive	$CaCl_2$ 4 wt%	Na_2CO_3 3 wt%
Compressive strength (MPa)						
-	19.4	29.6	34.6	20.3	31.5	36.7
1 day	19.8	29.9	34.8	20.7	32.0	37.2
3 days	20.5	30.5	35.0	21.5	32.5	37.6
7 days	21.2	31.3	35.2	22.2	32.9	37.9
14 days	21.7	32.5	35.3	22.3	33.1	38.3
28 days	21.9	33.0	35.7	22.8	33.3	38.6
60 days	24.2	35.6	35.7	25.3	36.9	38.6
90 days	26.4	37.6	35.7	27.8	40.5	38.6
Water absorption (%)						
-	8.30	7.13	6.18	7.98	6.69	5.34
1 day	8.92	7.67	6.40	8.53	7.01	5.74
3 days	9.69	8.15	7.39	9.01	7.74	6.38
7 days	10.40	8.76	7.80	9.70	8.60	6.95
14 days	11.43	9.59	7.96	10.15	9.01	7.43
28 days	11.71	10.10	8.25	10.54	9.27	8.27
60 days	12.52	10.44	8.50	10.97	9.65	8.43
90 days	12.86	10.62	8.61	11.16	9.83	8.50
Volume change (%)						
-	0.01	-0.01	0.01	0.01	0.03	0.05
1 day	0.05	0.01	0.03	0.03	0.04	0.06
3 days	0.10	0.03	0.05	0.05	0.07	0.09
7 days	0.22	0.07	0.09	0.12	0.09	0.11
14 days	0.27	0.12	0.15	0.15	0.10	0.11
28 days	0.29	0.16	0.19	0.16	0.10	0.12
60 days	0.33	0.17	0.21	0.16	0.10	0.12
90 days	0.36	0.17	0.22	0.16	0.10	0.12

Table 23. Effect of wetting/drying cyclic storage on the physical and mechanical properties of lime-containing composite materials activated by thermally and chemically accelerating method.

Properties	Lime mud 50%			Sludge waste 30%		
	Non additive	$CaCl_2$ 4%	Na_2CO_3 3%	Non additive	$CaCl_2$ 4%	Na_2CO_3 3%
Compressive strength (MPa)						
-	19.4	29.6	34.6	20.3	31.5	36.0
10 cycles	18.9	28.8	34.0	20.0	31.4	35.9
20 cycles	17.3	27.7	33.2	19.6	31.0	35.6
30 cycles	16.1	26.5	32.7	19.2	30.8	35.2
50 cycles	15.4	25.9	31.0	18.7	30.5	35.0
100 cycles	12.9	24.4	29.5	14.8	26.8	31.7
Bulk density (g/cm^3)						
-	1.46	1.65	1.68	1.47	1.70	1.73
10 cycles	1.46	1.64	1.68	1.47	1.70	1.73
20 cycles	1.45	1.64	1.67	1.46	1.69	1.72
30 cycles	1.44	1.63	1.67	1.46	1.69	1.72
50 cycles	1.43	1.62	1.66	1.45	1.70	1.71
100 cycles	1.40	1.61	1.65	1.43	1.66	1.70
Linear change (%)						
-	0	0	0	0	0	0
10 cycles	0.04	0.02	0.01	0.01	0.01	0
20 cycles	0.06	0.05	0.03	0.03	0.02	0.01
30 cycles	0.13	0.09	0.06	0.07	0.05	0.03
50 cycles	0.22	0.16	0.11	0.11	0.08	0.06
100 cycles	0.25	0.17	0.13	0.13	0.09	0.06

Table 24. Effect the combination of 3 accelerating methods on the physical and mechanical properties of lime- containing composite materials.

Properties	Lime mud 50 wt%			Sludge waste 30 wt%		
	Non additive	$CaCl_2$ 4 wt%	Na_2CO_3 3 wt%	Non additive	$CaCl_2$ 4 wt%	Na_2CO_3 3 wt%
Compressive strength (MPa)						
1 day	80.8	83.0	83.7	85.6	86.3	87.1
3 days	82.6	87.8	91.7	89.3	89.5	92.6
7 days	90.5	95.2	100.6	94.6	99.6	105.5
14 days	100.0	110.9	118.8	106.3	115.6	121.6
28 days	109.4	119.7	128.6	114.4	123.6	133.5
60 days	111.7	123.9	131.5	116.9	127.3	133.5
90 days	114.6	127.9	131.5	119.0	129.3	133.5
Bulk density (g/cm^3)						
1 day	2.14	2.15	2.16	2.15	2.16	2.17
3 days	2.15	2.16	2.16	2.16	2.16	2.17
7 days	2.16	2.17	2.18	2.16	2.17	2.18
14 days	2.18	2.19	2.21	2.18	2.19	2.20
28 days	2.20	2.21	2.23	2.20	2.23	2.25
60 days	2.20	2.21	2.23	2.20	2.23	2.25
90 days	2.20	2.21	2.23	2.20	2.24	2.25
Porosity (%)						
1 day	13.69	13.45	13.32	13.72	13.61	13.22
3 days	13.55	13.16	13.08	13.36	13.17	12.91
7 days	13.02	12.75	12.47	12.79	12.25	11.88
14 days	12.56	11.70	11.29	11.84	11.44	11.07
28 days	11.77	11.15	10.65	11.36	10.59	10.10
60 days	11.68	11.04	10.65	11.25	10.56	10.10
90 days	11.61	10.96	10.65	11.16	10.45	10.10
Volume change (%)						
1 day	-0.009	-0.008	-0.008	-0.006	-0.003	0.000
3 days	-0.003	-0.001	0.003	-0.004	0.000	0.001
7 days	0.002	0.005	0.008	0.002	0.003	0.006
14 days	0.006	0.009	0.013	0.003	0.005	0.007
28 days	0.010	0.015	0.019	0.003	0.006	0.008
60 days	0.012	0.016	0.19	0.003	0.006	0.008
90 days	0.013	0.17	0.19	0.003	0.006	0.008

Table 25. Effect of the combination of 3 accelerating methods on the performance under water of lime-containing composite materials.

Properties	Lime mud 50%			Sludge waste 30%		
	Non additive	$CaCl_2$ 4%	Na_2CO_3 3%	Non additive	$CaCl_2$ 4%	Na_2CO_3 3%
Compressive strength (MPa)						
-	110.6	117.6	128.6	114.4	122.3	133.5
1 day	111.1	118.8	128.9	115.4	123.7	133.8
3 days	112.4	119.8	129.4	118.0	124.7	134.3
7 days	113.6	120.9	130.5	120.3	125.5	134.5
14 days	115.7	122.1	131.1	121.8	126.2	134.8
28 days	118.6	123.8	131.6	122.8	126.6	135.0
60 days	118.9	124.5	131.6	123.4	127.6	135.0
90 days	119.2	125.1	131.6	123.5	128.4	135.0
Water absorption (%)						
-	3.47	3.17	3.05	3.09	2.86	2.61
1 day	3.76	3.27	3.05	3.40	2.87	2.61
3 days	4.07	3.28	3.06	3.66	2.87	2.63
7 days	4.19	3.33	3.06	3.70	2.88	2.63
14 days	4.51	3.35	306	4.18	2.88	2.63
28 days	4.57	3.35	3.08	4.36	2.88	2.64
60 days	4.64	3.34	3.08	4.45	2.88	2.64
90 days	4.73	3.34	3.08	4.49	2.88	2.64
Volume change (%)						
-	0.01	0.03	0.002	0.004	0.008	0.007
1 day	0.02	0.03	0.006	0.01	0.009	0.008
3 days	0.03	0.04	0.01	0.01	0.010	0.009
7 days	0.04	0.04	0.02	0.02	0.011	0.009
14 days	0.06	0.04	0.02	0.02	0.012	0.010
28 days	0.07	0.05	0.02	0.02	0.012	0.010
60 days	0.07	0.05	0.04	0.02	0.012	0.010
90 days	0.08	0.05	0.04	0.02	0.012	0.010

Table 26. Effect of wetting/drying cyclic storage on the physical and mechanical properties of lime-containing composite materials activated by the combination of 3 accelerating methods.

Properties	Lime mud 50 wt%			Sludge waste 30 wt%		
	Non additive	$CaCl_2$ 4 wt%	Na_2CO_3 3 wt%	Non additive	$CaCl_2$ 4 wt%	Na_2CO_3 3 wt%
Compressive strength (MPa)						
-	110.6	117.6	128.6	114.4	122.3	133.5
10 cycles	110.2	117.4	128.5	114.0	122.0	133.4
20 cycles	109.8	117.0	128.1	113.8	121.8	132.8
30 cycles	109.3	116.5	127.6	113.5	121.5	132.5
50 cycles	108.7	116.1	127.2	113.3	121.2	132.0
100 cycles	105.6	115.5	126.1	110.9	121.0	132.3
Bulk density (g/cm^3)						
-	2.19	2.21	2.23	2.21	2.22	2.25
10 cycles	2.19	2.21	2.23	2.21	2.22	2.25
20 cycles	2.19	2.20	2.23	2.20	2.22	2.25
30 cycles	2.18	2.20	2.22	2.20	2.21	2.24
50 cycles	2.18	2.20	2.22	2.20	2.21	2.24
100 cycles	2.17	2.20	2.22	2.19	2.21	2.24
Linear change (%)						
-	0	0	0	0	0	0
10 cycles	0	0	0	0	0	0
20 cycles	0.002	0.001	0	0	0	0
30 cycles	0.005	0.003	0.001	0.002	0.001	0.001
50 cycles	0.01	0.006	0.004	0.005	0.003	0.002
100 cycles	0.02	0.009	0.006	0.005	0.003	0.002

Vita

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