BÁO CÁO TẠI PHIÊN TOÀN THỂ

KEYNOTES

APPLICATION EXAMPLE OF HYDRATION HEAT MANAGEMENT OF MEGA FOUNDATION AND PUMPABILITY FOR HIGH PERFORMANCE CONCRETE USED IN SUPER HIGH RISE BUILDING

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ABSTRACTS: In case of constructing of super rise building (over 50 story) using high performance concrete as structural members, hydration heat management for mega foundation and pumpability of high strength concrete are very important construction technologies. In this paper, application examples of hydration heat management for mega foundation and pumpability of high strength concrete constructed in lotte center Hanoi (65 story) and Jamsil 2nd Lotte World (123 story) are introduced. The objective of this paper is to contribute practical experience and datum to the engineer who review construction method and quality management of high performance concrete when carry out similar super high-rise project with high strength concrete in the future.

KEYWORDS: High performance concrete, Mega foundation, Hydration heat management, Pumpability.

1. INTRODUCTION

1.1. Structural changes of high-rise buildings

High-rise buildings have traditionally been constructed with steel frames, but most of the highrise buildings have recently been constructed as a steel + RC complex, as the development of high-strength concrete mixing and the development of pump pressure equipment have enabled economical RC construction. Therefore, the main structure construction and quality assurance technology of high-rise structure using high-strength concrete is an essential technical element.

1.2. HPC element technology of high-rise buildings

The construction element technologies of highrise building using a high-strength concrete is summarized as table 1. In this paper, we will introduce the case of construction and hydration heat management of mat foundation using high performance concrete applied to the high-rise building in table 2, the case of construction and the quality control of the high-rise section.

Table 1. Key element technologies of HPC

Part	Main Tech.	Technical Details	
		· HPC Mix Design	
Material	HPC	· Fire Resistant Concrete	
	Design	· Mass Concrete	
		Hydration Control	
		· Concrete Pumping Plan	
Construction	Placement	· Placement Control	
		· ACS Optimization	

Table 2. Outline of high rise buildings by lotte E&C

	Lotte Center Hanoi	Lotte World Tower		
Picture		A		
Location	Hanoi, Vietnam	Seoul, South Korea		
Structure	RC + Steel	RC + Steel		
Scale	$B5\sim 65 F/272\ m$	$B6 \sim 123 F \ / \ 555 \ m$		



Figure 1. Structural type of high rise buildings by height [1]

2. CONSTRUCTION TECHNOLOGY OF MAT FOUNDATION

2.1 Overview and requirement performance of mat foundation

The basic outline and specification requirements for the construction of Hanoi and Jamsil skyscrapers are the same as Table 3. Concrete applied to the foundation of the super large mat was poured into the concrete using the SCC (Self Consolidating Concrete) as shown in the photo 1 according to the specification standard to improve workability and finishability.



Picture 1. Slump Flow evaluation (20-50-600)

The specification requirement performance includes concrete strength, type, maximum hydration heat value, and hydration heat measurement management for two months after pouring. The method of reducing hydration heat was applied considering the field conditions among the contents of table 4.

Table 4. Hydration reduction tech. of mat foundation

Part	Technical Details				
	Low Heat Concrete				
Material	Pre-mixed type binder				
	Setting retarder admixture				
	Surface insulation curing				
Construction	Upper and Low separation placement				

2.2 Hydration heat reduction methods

2.2.1. Low-heat concrete application (Method I)

As a hydration heat reduction method, the optimal mixture of concrete that can meet the strength standard while reducing the use of cement in the bonding materials and increasing the use of the admixture was finally decided through the process of Figure 2.

The concrete mixtures applied to the site is the same as Table 5, the admixture replacement rate is 80 % and 25%, respectively, and in Vietnam, only the fly-ash is used as a blast furnace slag supply problem.

Part	Lotte World Tower	Lotte Center Hanoi			
Plan	PI Jm(W)	15.700 17.5.700 17.5.700 17.5.700 17.5.700 17.5.700 17.5.700 17.5.700 17.5.700 17.5.700 17.5.700 17.5.700 17.4.000			
Size	71.7 × 71.7 × 6.5 m (31,203 m ³)	$44.1 \times 92.7 \times 5.7 \text{ m} (18,600 \text{ m}^3)$			
Strength	50MPa at 56 days	40MPa at 56 days			
Max temp.	71 $^{\circ}$ (Specification guideline)	80° C (Specification guideline)			
Control goal	below 25 °C between surface and center of mat concrete for 2 months				

Table 3. Overview of Mat Foundation

Table 5. Mix	proportion	of mat	foundation
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W/F		W/B S/a (%)		Unit Weight (kg/m ³)				AD1	AD2
		(%)	5/4 (70)	W	В	S	G	(B*%)	(B*%)
Jamsil	20-50-650	31.5	53.7	145	460	935	828	~1.3%	-
Hanoi	20-40-550	41.6	49.0	160	385	880	951	0.8%	0.4%

2.2.2. Pre-mix binder application (Method II)

In order to minimize the mixing deviation of different binders of the remicon factory mixer when replacing large amounts of admixture, cement, fly ash and blast furnace slag were supplied to the remicon factory as a premix type in the Jamsil site. [5]



Figure 2. Decision process of mix proportion

2.2.3. Setting retarder admixture application (Method III)

In the case of the Hanoi site, the mat concrete is poured for 53 hours continuously, so the lower concrete of the mat is hydrated, but the upper concrete is still pouring, so the temperature difference between the upper and lower is expected.

Therefore, in the case of lower concrete, a setting repeater admixture is applied to delay the generation of hydration heat, thereby reducing the difference between upper concrete and hydration heat.

2.2.4. Surface insulation curing (Method IV)

The temperature due to the concrete hydration heat is maintained for a certain period of time in the center, as shown in Figure 3, while the temperature of the surface is lowered by the heat release on the surface, resulting in a large internal and external temperature difference. In the field, surface insulation curing was performed until the temperature difference between the center and surface of mat foundation was less than 25 °C through center and surface temperature monitoring.



Figure 3. Hydration difference between surface and center of mat foundation

2.2.5. Applying different mixtures to the upper and lower part of mat foundation (Method V)

In the case of Hanoi, since the outside temperature is high, if the concrete of the mat foundation is poured for 53 hours continuously, the difference of hydration heat between upper part and lower part of mat is inevitably generated because the strength and hydration heat of initial pouring concrete(lower part) is generated but the late pouring concrete(upper part) is still in the process of pouring.

Therefore, in order to minimize the hydration heat generation time difference between the bottom and the upper of the mat foundation, the bottom part of mat foundation applied retarder admixture and the fly ash are replaced by 20% of total binders. On the other hand, the upper part concrete of mat foundation used a standard type admixture and 5% of total binders as a fly ash. As a result, the temperature difference between the upper and lower parts of the mat was managed to be less than 20 °C.



Figure 4. Separation placement of upper and lower part

2.3. Construction cases of mat foundation

The equipments used in the field, the time required for pouring, the method of applying the heat reduction of the hydration, and the temperature measurement result during the management period of concrete hydration heat after the pouring are summarized in the table 6.

Part	Lotte World Tower	Lotte Center Hanoi		
Placing method	One pour placement for 30hours (5,201 cars)	One pour placement for 42hours (2,433 cars)		
Equipments	14 Pump cars, 6 concrete Molies, 3 pumps.	12 pump cars, 3 pumps		
View				
Max Temperature	59.6°C at 48 hours later after placing	75°C at 53 hours later after placing		
ΔΤ	22.4°C (3months)/ Temperature crack index 1.12	16.2°C (3months)/ Temperature crack index 1.2		
Control method	Method I, II, IV	Method I, III, IV, V		
Curing view	19496/2011 18:10			
Strength	59.3MPa at 56 days	46.3MPa at 28 days		

Table 6. Summary of placement and curing method for mat foundation

3. HIGH PERFORMANCE CONCRETE PUMPING CONSTRUCTION IN HIGH RISE BUILDINGS

3.1. Overview and demand performance

High-strength concrete is placed with a pump into high flowable concrete to ensure finishability and construct easily. When concrete are pumped using pipeline, concrete is affected by the compressive force, friction force, temperature change, and selfweight as shown in figure 5, and concrete properties change. Quality and construction management are important because clogging phenomenon such as photo 2 occurs when the quality control of the produced ready-mixed concrete is insufficient or the concrete mix does not resist these external forces acting in the pipeline.



Figure 5. Working force on concrete during pumping [2,3,4]

Table 7. Key technologies of HPC Pumping

Part	Technical Details		
Mix Design	Optimization of mix proportion		
Equipment & Pipe-line plan	pumping simulation Equipment Pipe line plan		
Quality Control	Pressure monitoring Concrete testing		
Site Coordination	Coordination site and plant manpower coordination		



Picture 2. Pipeline blockage due to segregation

	Lotte World Tower	Lotte Center Hanoi
view		
Concrete grade	1) 20-70-650 (B6~ 43F: ~ 201 m) 2) 20-60-650 (44~ 76F: ~ 357 m) 3) 20-50-650 (77~123F: ~ 514 m)	1) 20-40-600 (41~65F: ~ 272 m) 2) 20-50-600 (33~40F: ~ 150 m) 3) 20-60-600 (B5~32F: ~ 80 m)
Pump	Putzmeister 14000SHP	Putzmeister 14000SHP
СРВ	Core 2 EA / Perimeter 3 EA	Core 2 EA/ Perimeter 3EA
Output	Lower part/Upper part : 40 / 30 m ³ /h	Lower part/Upper part : 55 / 40 m ³ /h
Required strength	over 14MPa 12hours later after placing	over 10MPa 12hours later after placing

Table 8. Overview of HPC pumping for high rise buildings

Table 9. Mix proportion of HPC

		W/B S/a	Unit Weight (kg/m ³)				AD	
		(%)	(%)	W	В	S	G	(B*%)
Jamsil	20-80-650	23.8	45.0	155	650	697	874	~1.8
	20-70-650	27.2	48.0	158	580	770	865	~1.5
	20-60-650	29.6	53.7	163	550	825	875	~1.3
Hanoi	20-60-600	28.6	45.0	163	580	741	939	~1.3
	20-50-600	32.0	47.0	165	522	788	922	~1.1
	20-40-600	37.4	48.0	160	452	836	941	~1.0

3.2. Quality Control Technology for High Performance Concrete Pumps

3.2.1. Mixture optimization of low viscosity concrete

High-strength concrete should be low viscosity for pump compression construction, but should be secured without separation of materials after pressing. We decided the optimal concrete mixtures to meet the required performance through the indoor mixing experiment and the mock-up test considering variables, the fineness modulus of fine aggregate and grain shape of coarse aggregate, water to cement ratio, in order to optimize the concrete mixtures.

The type and replacement rate of the blended cement was applied to 20% fly ash and 6% silica fume of all binders in terms of securing an early strength and economic efficiency in order to reduce the heat of the hydration and improve the workability in Jamsil site. The combination applied to Jamsil and Vietnam is the same as Table 9.

3.2.2. Equipment selection and pipeline design

The concrete piping plan and the type of pouring equipment were taken into account the diameter of the piping and the capacity of the pump, considering the maximum amount of drilling per day after joning the concrete pouring section. The equipment capacity adequacy was determined by pre-evaluation to determine whether the field-approved concrete mixtures satisfies the planned amount of discharge through pumping simulation for the maximum pumping distance planned on the site. A brief summary of the procedure is as follows figure 6.



Figure 6. Layout example of pump and pipeline

3.2.3. Concrete quality control

The quality control test of the concrete brought in to the site was carried out every 100m³ of the concrete from plant, and the initial physical properties of the concrete put into the high pressure pump hopper were visually confirmed and the initial management was carried out until the quality was stabilized through contact with the factory.

During the pouring, the high pressure pump management was based on indirect inspection of equipment and piping abnormalities through the discharge pressure, stroke time, and output quantity of placed concrete per hour.

In case of fresh concrete properties, the slump flow before and after the pumping (see Figure 7) showed an overall increase tendency in the range that satisfies the quality control standard.

In the case of hardened concrete properties, the strength of concrete tended to increase by about 16% on the 7th day after the pumping, 6% on the 28th, and 5% on the 56th. (Picture 8)



Figure 7. Slump flow change after placing through pipeline [6]



Figure 8. Strength change after placing through pipeline

Concrete discharge amount using the CPB was set $55 \text{ m}^3/\text{h}$ at the lower floors and 40 m³/h at upper floors for the 4-day cycle per floor in the Hanoi site. The actual discharge amount in the field is used with a low viscous concrete mix to secure workability that exceeds the target standard as shown in Figure 9.

For the 4-day cycle per floor, the concrete strength should be at least 10MPa for ACS foam lifting after 12 hours after pouring.

Figure 10 shows the 7-day compressive strength data after pouring concrete at the Hanoi site, which can provide early concrete compressive strength except for some periods during the winter season.



Figure 9. Discharged amount of pumped concrete per hour



Figure 10. Compressive strength at 7 days

3.2.4. Field management

In order to minimize the blockage of concrete in the pipeline during pumping, the concrete quality manager checks the abnormality through the visual inspection of all agitator vehicles before the hopper input. In addition, it is important to manage the waiting time during concrete pouring through the management of the delivery vehicles to the field, the layout plan to install the horizontal pipeline, and the stability of the form pressure.

4. CONCLUSIONS

4.1. High performance concrete mixture and quality control technology

1) The raw materials used in high-performance concrete should use high-quality raw materials considering the concrete quality requirements. In addition, when selecting a multi-remicon factory in the city, it is necessary to secure uniform concrete quality through the selection of materials considering quality control efficiency.

2) In the case of high-rise buildings, the mixtures considering the various kinds of concrete grade by height and member should be reviewed in advance. In order to streamline the quality control of ready-mixed concrete, it is necessary to simplify the concrete grade as much as possible, improve the performance of high-range water reducing agent and require supervisory curing management.

3) In order to minimize the pipe obstruction phenomenon and quality fluctuations during the construction of high-performance concrete, it is necessary to immediately cope with quality fluctuations by improving understanding of the characteristics of ready-mixed concrete between producers, contractors and quality managers and improving the proficiency of visual quality control.

4.2. Mat foundation construction technology

1) In order to manage the temperature crack of the mat foundation of high-rise buildings, it is necessary to review the necessary technologies in accordance with the field conditions among the hydration heat management technologies in advance and establish the construction plan and quality control plan.

2) In case of continuous pouring for more than 30 hours, quality-oriented construction plan should be established through pre-remicon factory inspection, raw material supply and quality control, hourly production according to remicon factory, and management of placed concrete in order to minimize the variation of concrete quality.

4.3. High performance concrete pumping construction technology in high rise building

1) Because high-rise pumping equipment has a lot of pressure on piping, periodic piping thickness management is necessary for places where friction is expected, such as curved pipes. In addition, for successful concrete pouring, equipment management technology of equipment skilled worker and quality control technology of ready-mixed concrete are required.

2) Low-visity concrete mixture and curing management are needed to shorten the construction period of high-rise building frames and to secure early deformation of formwork and hourly discharge.

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EFFECT OF CURING REGIME ON SYNTHESIS ABILITY AND PROPERTIES OF RED MUD BASED GEOPOLYMER

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ABSTRACTS: Red mud can be used in combination with other materials containing active silicon dioxide to produce geopolymer because silicon dioxide in red mud does not dissolve in alkaline solution. The test results presented in this paper show that high pressure treatment in autoclave can dissolve part of silicone dioxide of red mud and initiate geopolymerization. Compressive strength of red mud based geopolymer can reach 10.6 MPa with softening coefficient over 0.70. Adding active silicon dioxide supplement by using fly ash in replacement of 26.3% red mud can increase compressive strength of geopolymer up to 20 MPa and softening coefficient more than 0.90. Futhermore, geopolymerization in high pressure condition can reduce residual sodium hydroxide and lower pH value of geopolymer. As the result, pure red mud and fly ash adding red mud geopolymers meet the technical requirements and can be used for manufacturing masonry units.

KEYWORDS: Geopolymer, autoclave, red mud, fly ash, compressive strength.

1. INTRODUCTION

The production of alumina from bauxite in Bayer's technology in Vietnam poses a major environmental challenge in treating red mud waste. Recently, red mud was investigated to be recycled in many ways, among that using red mud to produce building great materials has attracted attention from researchers. Red mud is used in the production of baked clay bricks, in the manufacture of cement, concrete, especially in geopolymer materials, just to name a few. The studies [1-4] have focused on the influence of some factors on geopolymerization and the properties of geopolymers using red mud.

In [1], the effect of red mud in fly ash based geopolymers was investigated. The result showed that geopolymerization improvement can be achieved by using up to 40% of red mud in the total amount of However, the strength geopolymers. of the geopolymer is only improved with the volume of red mud in the range of 5% to 20%. The reaction rate depended on the NaOH concentration, but the mechanical properties depended not only on NaOH concentration, but also on other factors such as dissolution ability of silicate and the presence of iron oxide. In [2], red mud was used up to 20% by weight with activated fly ash in NaOH solution and curing at 80°C. Result showed a significant effect of aluminate content and amorphous silicate as well as particle size of fly ash to the properties of the geopolymer.

He J. [3] used red mud with fly ash, rice husk ash to produced geopolymers. He used 20% to 80% of red mud combined with activated fly ash in the solution

of water glass 1.5M and NaOH to achieve geopolymers with compressive strength of 13 MPa to 7 MPa, respectively. Geopolymer with compressive strength of 20.5 MPa can be produced by adding 30% to 60% rice husk ash by weight to red mud and 2M to 6M NaOH solution. Smita S. et al. [4] used the 30% to 90% red mud with fly ash and GBFS activated in 6M to 10M NaOH solution and achieved geopolymers with compressive strength from 9.4 MPa to 35.8 MPa.

In the above studies, red mud was used in combination with a material containing active silicate and aluminate, thus red mud did not play the decisive role in geopolymerization reaction. The results also showed that the higher red mud content in geopolymers, the lower strengths of geopolymers were. The SiO₂ in the red mud did not participate in geopolymerization because it was insoluble in NaOH. Al₂O₃ and Fe₂O₃ were soluble in NaOH but they had different effects on geopolymerization. While Al₂O₃ contributed to the polymer chains and played possitive role, Choi S.C. and Lee W.K. [5] suggested that Fe₂O₃ inhibits the geopolymerization of mine tailing, melting slag, and alkali activator. Adding 5% Fe₂O₃ by volume could lead to compressive strength reduction of the geopolymer from 73.6 MPa to 32.5 MPa.

Incresement of the alkaline concentration of activator could help to enhance the geopolymerization reaction thus lead to the increasement of compressive strength of the geopolymer. However, higher alkaline concentration of activator caused higher soluble alkaline residual content in geopolymer and higher risk of efflorescence (formation of sodium carbonate heptahydrate $Na_2CO_3.7H_2O$ on or near the surface of the material). Proper selection, proportioning of materials and high temperature curing can reduce the efflorescence but could not totally resolve the problem [6].

The composition of the red mud depended on the plant and comprised of Fe₂O₃ (30%-60%), Al₂O₃, (10%-20%), SiO₂ (3%-50%), Na₂O (2%-10%), CaO (2%-8%) and other oxides with about 20%-30% amorphous phase. The fact that red mud contains components needed for geopolymerization reactions such as SiO₂, Al₂O₃ and Na₂O. However, SiO₂ could not be activated by alkaline solution in atmospheric pressure conditions, thus geopolymerzation was not conducted.

It was shown in [7] that under high pressure and high temperatures in autoclave, crystalline SiO_2 may also be involved in the formation of new substances. This technology has also been used by some researchers for geopolymer materials [8-10].

The study by Kriven WM [8] on geopolymers using metakaolin and silica fume activated by NaOH and KOH solutions with reinforced fiber under high pressure, high temperature curing conditions showed that geopolymers structure became denser than under atmospheric pressure condition.

Kani et al. [9] produced geopolymers from nature puzzolan with a compressive strength of 108.7 MPa after high pressure treatment within 30 hours at 210°C following curing for 7 days at room temperature and atmospheric pressure. Meanwhile, the maximum strength was only 57,5 MPa when curing at 85°C and in atmospheric pressure condition.

Hanayneh B. [10] studied the effect of the curing pressure on the properties of geopolymers using metakaolin and quartz sand activated by NaOH. The results showed that the curing pressure has a major influence on the structure formation and properties of the geopolymer. The treatment of geopolymers including sample drying, high pressure curing and post-drying, allowed to increase geopolymer strength by 25%.

Researches on the influence of autoclave curing on red mud based geopolymer were limited. However, it could be assumed that the high pressure, high temperature curing in autoclave could activate SiO_2 in red mud using available residuing NaOH solution, creating a premise for geopolymerization. Thus, it is possible to utilize all needed materials in red mud to produce geopolymers without using additional materials. To improve the properties of the geopolymer from the red mud, it is possible to add alkalis and amorphous SiO_2 containing materials such as fly ash, silicafume. Geopolymer from red mud can be used in manufacturing a variety of construction materials. For unbaked brick production, the geopolymer material should reach compressive strength over 7.5 MPa and a softening coefficient above 0.8.

2. MATERIALS AND METHODS

The red mud used in our study was from the Tan Rai alumina plant. The Tan Rai alumina plant also operates a coal-fired thermal power plant with a capacity of 30 MW, from which the fly ash was used as SiO_2 supplement material for geopolymerization.

The composition and properties of these materials are shown in Table 1.

No	Characteristic	Materials			
INO.		Red mud	Fly ash		
1	Density, g/cm ³	3,47	2,20		
2	Bulk density, kg/m ³	685	905		
3	Mean particle size, µm	9,5	48,2		
	Oxide content, %				
	- SiO ₂	7,40	47,74		
	- Al ₂ O ₃	13,65	35,36		
	- Fe ₂ O ₃	56,05	7,02		
4	- Na ₂ O	3,63	0,69		
	- K ₂ O	0,25	0,41		
	- CaO	3,10	4,20		
	- TiO ₂	0,15	0,43		
	- L.O.I	12,50	3,85		

Table 1. Characteristic of raw materials

The acid-soluble Na₂O content presented in Table 1 is determined according to TCVN 141:2008 [11]. However, the water-soluble Na₂O content in red mud and fly ash were 0.664% and 0.010%, respectively when tested according to TCVN 6882:2001 [12]. X-ray diffraction analysis (Fig. 1) showed that red mud contained 21% goethite (FeOOH), 14% hematite (Fe₂O₃), 5% gibbsite (Al(OH)₃) and 60% amorphous phase. Fly ash contained 20% mullite (Al₆Si₂O₁₃), 2% quartz (SiO₂) and 78% amorphous phase.



Figure 1. XRD spectrum of red mud and fly ash

The 97%-98% purity NaOH solid was from the Bien Hoa Chemical Company. Determination of the SiO_2 and Al_2O_3 dissolution ratios was carried out based on dried red mud and dried fly ash by using a 0.09 mm sieve. 2.5 g of the sample was then added to the reactor with 25 ml of NaOH solution with different concentration. To determine the oxides dissolution ratios of fly ash, we compensated the amount of Na₂O to match the amount of Na₂O in red mud. The reaction was carried out under different conditions following by an analysis to determine the dissolution oxides.

Geopolymers mixture was made by mixing ingredients in a predefined proportion. A 90x80x40 mm geopolymer sample was made by semi-dry pressing under 10 N/mm². The samples were molded and put into high temperature curing or autoclave curing conforming to the prescribed regimes. During autoclave curing, the pressure acceleration and deceleration were constantly kept. The corresponding maximum pressure and temperature as well as the isothermal time were changed according to the experimental plan. After high pressure curing, the sample was maintained in a room for 28 days.

Compressive strength of the geopolymer was determined according to TCVN 6477:2016 [13] but no conversion coefficient was applied. Softening coefficient was determined using formula in TCVN 7572-10:2006 [14]. The pH value of the geopolymer was determined according to TCVN 9339:2012 [15]. The residual alkali in the geopolymer was determined according to TCVN 6882: 2001 [12] using grinded geopolymer powder.

3. INFLUENCE OF CURING REGIME TO DISSOLUTION ABITILY OF SIO₂ AND AL₂O₃

The dissolution process of SiO_2 and Al_2O_3 plays an important role in the geopolymerization process and critically affects the properties of geopolymer This study investigated the solubility of the above oxides in red mud and fly ash under different pressure and temperature conditions. Table 2 and Table 3 show dissolution ratios of oxides under high temperature curing in atmospheric pressure and autoclave curing conditions, respectively.

The results showed that in high temperature curing regime SiO_2 in red mud did not dissolve when the NaOH solution was added at a concentration of 1M to 15M. The dissolution process was also not activated when the reaction temperature increased from 80 °C to 200 °C. Meanwhile, the dissolution ratio of SiO₂ of fly ash after 24 hours at 80 °C sharply increased from 2.33% to 15.21% when increasing the NaOH concentration from 1M to 15M. Raising the reaction temperature from 80 °C to 200 °C increased the soluble SiO₂ content of fly ash by a smaller rate.

With a reaction time of 10 hours, this ratio increased from 3.23% to 4.37%. When heating without adding NaOH, a certain amount of SiO₂ was also dissolved since the materials already contained Na₂O.

Table 2. Dissolution ability of SiO2 and Al2O3under high temperature curing

Curing regimes		NaOH	Dissolution ratio, % of				
T,	τ,	conc.	Red	mud	Fly	ash	
°C	h	auu.	SiO ₂	Al_2O_3	SiO ₂	Al_2O_3	
80	24	1M	0,00	4,13	2,33	4,56	
80	24	3M	0,00	4,74	4,58	4,66	
80	24	5M	0,00	4,76	8,66	4,70	
80	24	7M	0,00	4,76	10,65	4,76	
80	24	9M	0,00	4,76	13,68	4,76	
80	24	11M	0,00	4,76	14,98	4,76	
80	24	13M	0,00	4,76	15,15	4,76	
80	24	15M	0,00	4,76	15,21	4,76	
50	10	-	0,00	1,20	1,06	1,47	
100	10	-	0,00	2,20	1,41	2,41	
150	10	-	0,00	2,26	1,75	2,48	
200	10	-	0,00	2,29	2,20	2,56	
50	10	1M	0,00	1,74	2,23	2,11	
100	10	1M	0,00	2,95	3,65	3,14	
150	10	1M	0,00	3,02	4,10	3,88	
200	10	1M	0,00	3,22	4,37	4,25	

SiO₂ in the red mud began to dissolve when we increased the pressure (Table 3). The dissolution ratio of SiO₂ of red mud after 10 hours isothermal curing in from 0.34% autoclave increased to 2.25% corresponding to the pressure increasement from 0.4 MPa to 1.6 MPa. At a constant pressure of 1.2 MPa, SiO₂ dissolution ratio increased from 1.46% to 2.71% as a result of raising time from 4 hours to 16 hours. Adding of NaOH under autoclave curing conditions also increased the SiO₂ dissolved in red mud. The experimental results also showed that, under autoclave curing, the dissolution ratio of SiO₂ of red mud reached and exceeded the dissolution ratio of SiO₂ of fly ash when using a solution with the same NaOH concentration under high temperature curing. This is a significant finding allowing us to predict that red mud can be involved in under autoclave curing geopolymerisation like fly ash under atmospheric pressure curing.

High pressure curing in autoclave also affected to the SiO₂ dissolution ratio increasement of fly ash. The dissolution ratio of SiO₂ was significantly increased when we raised either pressure or isothermal curing time. Increasing the pressure to 1,6 MPa can double the ratio (from 4.37% to 8.45%) after 10 hours curing at 201°C and with 1M NaOH. To achieve the same SiO₂ dissolution ratio, we tried to reduce the level of consumed NaOH by putting more pressure to activate the material. This not only saved raw materials costs but also improved work and environmental conditions by reducing the amount of consumed NaOH. Futhermore, fly ash can be used to replace part of the red mud to provide more active SiO₂ source for geopolymerization hence improve the properties of the material.

Table 3. Dissolution ability of SiO₂ and Al₂O₃ under autoclave curing

Curing regimes			NaOH	Dissolution ratio, % of				
P, MPa	T, ⁰C	τ, h	conc. add.	Red mud		Fly ash		
				SiO ₂	Al_2O_3	SiO ₂	Al_2O_3	
0,4	144	10	-	0,34	3,87	1,94	5,22	
0,8	170	10	-	1,05	5,65	6,75	8,25	
1,2	188	10	-	2,18	7,22	7,58	13,65	
1,6	201	10	-	2,25	8,12	8,18	16,58	
1,2	188	4	-	1,46	5,74	6,86	8,69	
1,2	188	8	-	1,95	6,25	7,08	11,88	
1,2	188	12	-	2,22	7,48	7,84	15,88	
1,2	188	16	-	2,71	8,35	8,94	16,87	
0,4	144	10	1M	1,28	4,25	8,34	6,25	
0,8	170	10	1M	1,87	6,25	9,69	10,25	
1,2	188	10	1M	2,38	7,98	11,65	16,35	
1,6	201	10	1M	2,89	8,45	13,72	20,25	
1,2	188	4	1M	1,95	6,42	10,33	10,33	
1,2	188	8	1M	2,08	7,02	11,46	13,65	
1,2	188	12	1M	2,44	8,33	13,00	17,98	
1,2	188	16	1M	2,98	9,03	18,25	20,33	

Unlike SiO₂, aluminum oxide Al₂O₃ in red mud and fly ash can be dissolved in any condition. At atmospheric pressure conditions, the solubility of Al₂O₃ was less dependent on the concentration of NaOH. Raising the NaOH concentration from 1M to 15M, after 24h at 80°C, the Al₂O₃ dissolution ratio of red mud and fly ash increased from 4.13% to 4.76% for red mud and from 4.56% to 4.76% for fly ash. However, the increasement was not linear. The Al₂O₃ ratio did not change when NaOH concentration increased from 5M to 15M for red mud and from 7M to 15M for fly ash. Increasing curing temperature significantly raised the solubility of Al_2O_3 . This is proved by the fact that when the curing temperature increased from 50°C to 200°C, after 10 hours curing, the soluble Al_2O_3 content of the red mud increased from 1.20% to 2.29% without addition of NaOH, and from 1, 74% to 3.22% when the NaOH concentration was 1M. The corresponding values for fly ash were from 1.47% to 2.56% and from 2.11% to 4.25%, respectively.

At autoclave curing, the Al_2O_3 solubilities of both red mud and fly ash were significantly improved. The solubility of Al_2O_3 improved with increasing pressure and isothermal time. In addition, in this condition, increasing the NaOH concentration also significantly increased the proportion of Al_2O_3 dissolved. The results showed that in autoclave curing condition, the soluble Al_2O_3 content of fly ash and red mud could reach 20.33% and 9.03%, respectively.

These results showed that it is possible to use the autoclave curing to activate the components in the red mud to create a precondition for the geopolymerization reaction.

4. INFLUENCE OF CURING REGIME TO CHARACTERISTIC OF RED MUD BASED GEOPOLYMER

Research on the effect of curing conditions to the properties of geopolymers was conducted with mixtures containing only red mud and mixtures of which 26.3% of red mud was replaced by fly ash. The solids to liquid ratio was chosen in accordance with the forming method and was equal to 0.2.

In this study, we also produced geopolymer samples by only using red mud (i.e., without adding fly ash) and curing at high temperature in atmospheric pressure. The samples were not hardened and lost strength when soaking into water. This result is trivial and will not be discussed here. Again, this finding reconfirmed the fact that the red mud itself does not have the ability to self-hardening in atmospheric pressure curing condition through geopolymerization due to the absence of active SiO₂.

Further studies were carried out with a mixture of red mud with fly ash supplementation. High temperature curing regimes in atmospheric pressure and geopolymer properties are shown in Table 4.

Geopolymers using red mud were only hardened at atmospheric pressure when it contained dissolved SiO_2 by adding fly ash. The results in Table 4 show that with the same fly ash content, raising the curing temperature from 50°C to 200°C did not significantly increased the compressive strength of the geopolymer. Without adding suplemental NaOH, available alkali in the red mud could also triggered geopolymerization. The compressive strength of geopolymer reached 6.9 MPa when curing at 200°C for 10 hours. However, the geopolymer's softening coefficient was relatively low (below 0.46). The material was not durable in water saturated condition possibly due to the low degree of geopolymerisation and lack of cohesion. By adding NaOH, the strength of the geopoymer was significantly improved, reaching 9.6 MPa after 10 hours of heating at 200 °C. Softening coefficient was also improved, but only to 0.57. This limitation impeded the practical application of geopolymer, hence autoclave treatment should be applied to provide additional active SiO₂.

 Table 4. Properties of geopolymer under high temperature curing

Curing regimes		NaOH conc.	R _n , MPa	Soft.	pН	Na ₂ O residual,
Т, ⁰С	τ, h	add.	1011 u	00011.		%
50	10	-	6,1	0,39	9,91	0,42
100	10	-	6,2	0,40	9,90	0,42
150	10	-	6,4	0,42	9,90	0,40
200	10	-	6,9	0,46	9,88	0,40
50	10	1M	9,0	0,51	10,40	0,51
100	10	1M	9,3	0,53	10,39	0,49
150	10	1M	9,6	0,56	10,38	0,48
200	10	1M	9,6	0,57	10,38	0,46

We also performed a study on autoclave curing with the use of red mud and a mixture of red mud and fly ash. When using red mud without adding fly ash, we achieved geopolymer with 10.6 MPa with softening coefficient 0.66 after 10 hours autoclave curing at pressure 1.6 MPa and temperature 201°C. When we gradually added 1M, 2M, 3M of NaOH solutions, the strength of geopolymer did not change much but the softening coefficient was slightly improved and reached 0.71. This observation showed that the geopolymerization process took place by solely using red mud and there was no need to have other material except mixing water. It is arguably believed that the geopolymer can be used as a building material in less-water-affected areas. However, to improve the properties of geopolymers, it is necessary to optimize the curing regime or add supplemental active SiO₂ from external sources.

In our subsequent experiments, active SiO_2 was added by replacing 26.3% of red mud with fly ash. The autoclave curing regime and geopolymer properties are shown in Table 5.

Experiments with the red mud - fly ash mixture showed that the properties of the geopolymer were significantly improved. With the geopolymer formed

from a mixture of red mud and fly ash without adding NaOH, the pressure increased from 0.4 MPa to 1.6 MPa. The compressive strength increased from 7.4 MPa to 14.2 MPa after 10 hours isothermal curing. Increasing curing time also significantly improved compressive strength of geopolymer. With a fixed pressure of 1.2 MPa, when we increased the curing time from 4 hours to 16 hours, the compressive strength of geopolymer raised from 11.0 MPa to 15.3 MPa. In these experiments, the geopolymerization was entirely based on leftover alkali in the red mud. After reaction, the amount of residual Na₂O decreased significantly and had a value not exceeding 0.23% (minimum value of 0.14%) compared to 0.51% (minimum value of 0.40%) when curing in atmospheric pressure condition. The pH value of the geopolymer after autoclave treatment was lowest at 8.99 compared with 9.88.

Table 5.	Properties	of	geopol	ymer
un	der autocla	ve e	curing	

Curing regimes			NaOH	D	Soft		Na ₂ O
P, MPa	T, ⁰C	τ, h	conc. add.	к _n , MPa	coeff	рН	residual, %
0,4	144	10	-	7,4	0,61	9,58	0,23
0,8	170	10	-	10,6	0,73	9,52	0,20
1,2	188	10	-	12,7	0,84	9,22	0,15
1,6	201	10	-	14,2	0,91	9,09	0,14
1,2	188	4	-	11,0	0,75	9,39	0,17
1,2	188	8	-	12,0	0,76	9,23	0,16
1,2	188	12	-	13,9	0,86	9,18	0,15
1,2	188	16	-	15,3	0,90	8,99	0,14
0,4	144	10	1M	11,3	0,62	9,75	0,35
0,8	170	10	1M	14,7	0,76	9,68	0,33
1,2	188	10	1M	17,4	0,85	9,58	0,23
1,6	201	10	1M	19,1	0,92	9,48	0,20
1,2	188	4	1M	15,2	0,76	9,59	0,30
1,2	188	8	1M	16,9	0,80	9,58	0,23
1,2	188	12	1M	18,7	0,86	9,56	0,22
1,2	188	16	1M	20,1	0,91	9,52	0,20

When NaOH is added, the properties of the geopolymer were improved. With the same curing regime, when adding 1M NaOH the compressive strength of geopolymer was from 11.3 MPa to 20.1 MPa (i.e. increased by 35% and 50%). However, the softening coefficient of the geopolymer did not change significantly as the NaOH concentration increased.

Softening coefficient of geopolymer linearly increased with isothermal curing time and curing

pressure. The compressive strength of the geopolymer was reduced at the water saturated condition compared to dry condition due to the additional stress that occured when the water penetrated into cracks and defective locations. Therefore, the softening coefficient also can be used to evaluate the defective degree of structure. We realiazed that the structure of geopolymer was less defective after autoclave curing conditions. According to [16], when the softening coefficient is greater than 0.8, the geopolymer can be considered as water durable material and can be used in wet areas. To produce a water durable geopolymer, the red mud - fly ash mixture should be cured for 10 hours and no less than 12 hours with pressure higher than 1.0 MPa and 1.2 MPa, respectively. With these curing conditons, the compressive strength of the geopolymer can be reached 10 MPa, which is suitable for use as masonry unit. We recommend this curing condition for practical application.

When adding NaOH, the geopolymer had higher compressive strength but the leftover amount of alkali increased to 0.38% (minimum value of 0.20%). However, this was still smaller than residual alkali after high temperature curing in atmospheric pressure condition. Similarly, the pH value of the geopolymer when adding NaOH ranged from 9.5 to 9.8, but it was lower than the pH of the geopolymer under high temperature curing (about 10.4).

To study the effect of curing regime on the geopolymer composition, XRD analysis of samples under different curing regimes (Fig. 2) were performed.



Figure 2. X-Ray spectrum of geopolymer under high temperature curing (A) and autoclave curing (B) conditions

In addition to SiO_2 and Al_2O_3 , there is a certain amount of CaO in the raw material. This CaO can react with the silicate to form a new mineral such as CSH. However, the XRD spectrum analysis revealed no new mineral was appeared in the geopolymer. Therefore, we can emphasise the possibility of strength development was entirely based on geopolymerisation. In the XRD spectrum of geopolymer samples under high temperature curing condition we were still able to detect characteristic peaks of mullite (at $2\theta =$ 16.5, 26.5, 27, 32.8, 35; 41) in fly ash, gibbsite (at 2θ = 18.5) and goethite (at $2\theta =$ 21.2; 36.8) in red mud. However, we were unable to detect characteristic peaks in the autoclaved geopolymer sample. We believed that these minerals had been dissolved under high pressure conditions to participate in the geopolymerization process.

It is possible to calculate the total amount of dissolved SiO₂ and Al₂O₃ as well as the ratio of two oxides for each mixture in each curing regime based on (i) the mixture proportion (73.7% red mud and 26.3% fly ash), (ii) the content of dissolved SiO_2 and Al₂O₃ in red mud, and (iii) fly ash in the corresponding curing regime (Table 2 and Table 3). By studying the correlation of these parameters with the compressive strength of the geopolymer, we suggested that the active SiO₂ content is closely correlated with the compressive strength of the geopolymer (Fig.3). We also determined the regression equation describing the relationship for the case of high temperature and autoclave curing by using the least squares method. The result showed that the compressive strength of the geopolymer is linear, co-variable with the total content of dissolved SiO₂ in the mixture.





Davidovits [17] showed that the structure of the geopolymer depends on the ratio of SiO_2 to Al_2O_3 . The product will be poly (sialate), poly (sialate-siloxo), poly (sialate-disiloxo) and a Si-O-Al bond between two other polymer chains when the ratio is 1, 2, 3 and more than 3, respectively. These types of polymer products will determine the structure and properties of the geopolymer.

In our study, the ratio between the red mud and the fly ash were fixed (we had a fixed SiO_2/Al_2O_3 ratio of 0.93 in terms of total oxide). High temperature

or autoclave curing did not change the ratio of total oxide but only ratio of dissolved oxide. The greater the amount of dissolved SiO_2 were, the more polymer chains contributing to the structure and compressive strength of geopolymer were formed.

In Figure 3, the total amount of dissolved SiO_2 after high temperature curing is relatively low, corresponding to compressive strength of geopolymer is not exceeding 10 MPa. Autoclave curing promoted more dissolved SiO_2 up to total of 120 kg/m³ which significantly improved the compressive strength. The regression equation is based on the data of both cases of the form:

$$R = 0,123 \times (SiO_2)_{atv} + 5,967 \tag{1}$$

Equation (1) has $R^2 = 0.954$, indicating an accurate correlation. This shows that the correlation between the compressive strength and the total amount of dissolved SiO₂ can be applied to the geopolymer materials independently of the curing conditions. Based on that, Figure 3 can be used to select the proportion of the geopolymer mixture according to the required compressive strength.

5. CONCLUSION

The curing regime had a great influence on geopolymerization as well as the properties of geopolymer using red mud. Unlike high temperature curing in asmospheric pressure, autoclave curing made it possible to dissolve more SiO_2 in red mud. The level of solubility of the oxides as well as the properties of the geopolymer using red mud was significantly improved by increasing the curing pressure, the isothermal time and the concentration of NaOH solution.

Red mud can be used independently or in combination with fly ash and NaOH to make geopolymers. Geopolymer using red mud can achieve compressive strengths of up to 10.6 MPa, softening coefficient of 0.70. With the addition of active silica by replacing 26.3% red mud with fly ash, the compressive strength of the geopolymer reached 20 MPa with a softening coefficient greater than 0.90. In addition, geopolymer synthesis at high pressure also reduced the residual alkali and pH of geopolymer. We also proposed reasonable curing regime to apply in practical production.

Autoclaved geopolymer based on red mud or a mixture of red mud and fly ash met the technical requirements and can be used in the production of masonry unit.

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NOVEL LIGHTWEIGHT MATERIALS FOR PREFABRICATED MODULAR CONSTRUCTION

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ABSTRACT: Cellular concrete or foam concrete has been recently utilised for prefabricated modular construction. The application of highly porous concretes in prefabricated modules brings some advantages to the construction industry, such as improving the fire resistance, thermal and acoustic insulation properties, construction efficiency and housing affordability. In order to control the properties of foam concretes and predict their performance for various prefab applications, it is necessary to understand and measure their characteristics. To this effect, recent advancements in concrete foam technology and their applications for prefabricated modular construction have been explored. With a combination of advanced characterisation techniques, the properties of foam concretes can be customised for specific construction applications. Knowledge on effective techniques for manipulating the characteristics of foam concretes facilitates the application of novel materials and the development of high-performance prefabricated modules.

1. INTRODUCTION

Structural insulated panels (SIP) or insulated sandwich panels are usually three-layer systems that are made of two outer shells of high strength materials with a lightweight, low-density core material separating them (Figure 1). SIPs are ideal for prefabricated construction. Forest Product Laboratory (FPL) introduced SIP in 1935 and the first commercial SIP was produced in 1952⁻¹. This development sparked growing interest in developing and advancing SIPs in terms of improving their properties, reducing costs and exploring environmentally friendly options.



Figure 1. SIP with two hard shells that sandwich a lightweight foam core

In sandwiching a soft core between strong, thin facets, the combined properties of the sandwich panel possess many advantages over its monolithic counterpart, such as high strength and toughness, rapid assembly from cost-effective and lightweight building materials, and so on. The lightweight feature of SIP panels is particularly attractive because this permits ease of handling and assembly. The special design of these panels facilitate a significant reduction in construction time, effective acoustic and thermal performance, utilisation of recyclable materials, reduction of the maintenance cost of buildings and extension of their design life. The application of SIPs in construction can also improve housing affordability.

Carbon or glass fibre reinforced polymer composites (CFRP/GFRP) have been used from the mid 1980s as the stiff skin of SIPs, together with a lightweight and softer core typically made of polymeric foams such as PVC foams^{2,3}. FRP sandwich panels have limited applications due to their low stiffness and high cost. Steel shell sandwich panels with a polyurethane infill core was developed later to expand the application of SIPs by increasing the stiffness of the panels⁴. However, the durability of the panels at elevated temperatures was still a concern in these panels. The core of SIPs is generally made of lightweight materials such as polyisocyanurate foam (PIR), expanded polystyrene (EPS) and polyurethane foam (PUR)⁵. EPS is still the most common core in the market and is widely used in Australia. One of the disadvantages of the polymeric core in SIPs is its susceptibility to elevated temperatures as most of these foams are combustible. In the 1990s, whole metal SIPs were introduced ⁶. A ribbed metal structure (e.g. honeycomb) replaced the lightweight core, and the metal skins were welded to the core by laser welding technology. While the stiffness, consistency and accuracy of the SIP designs were massively improved by this technique, the impact resistance of SIP was still not acceptable and they could be perforated ⁷. Various materials have been introduced to be used in SIPs (Figure 2). The honeycomb cores usually offered superior performance compared to foam cores but their price was also much higher, which limited their adoption in practice⁸.





Concrete was later used in prefabricated modules as an alternative core material for SIPs with improved properties ⁹. Concrete has relatively low cost, high durability and a long service life, which makes it ideal for prefab modular construction ¹⁰. Lightweight concrete has been used as the core of SIPs with FRP or steel skins (Figure 3) and these panels have been utilised for many prefab applications such as insulated wall panels, hybrid slab systems, bridge decks, anticollision structures, impact resisting structures, volcanic shelters, submerged tube tunnels and offshore deck structures ^{10, 11, 12, 13}. The combination of a steel shell and lightweight concrete core combines the advantages of both elements, and this has been proven to offer high protection against fire, impact and blast loads ¹⁴. The smooth steel skin of SIP acts as impermeable reinforcement and formwork for the panel, which is impact resistant and can easily be inspected and maintained during its service life¹⁵. Geopolymer foam concretes have also been found to be a more environmentally friendly option for construction industry ^{16, 17}.



Figure 3. Lightweight SIP with steel shell and foam concrete core (http://speedpanel.com.au/)

Lightweight concrete with densities lower than 2000 kg/m³ have been manufactured using a variety of techniques, which result in different physical structures ¹⁸. One of the methods for developing light weight concrete involves utilising lightweight aggregates ¹⁹, which creates solid samples with densities as low as 1580 kg/m³. However, further reductions in the density of concrete can be achieved by utilising techniques such as aerating concrete ²⁰ and entrapping foam in concrete, and both methods result in a cellular microstructure. Patented by Aylsworth and Dyer in 1914²¹, foam concrete is a lightweight concrete with a high volume of voids. Cementitious binders, water and aggregate are the main components of foam concrete, which is similar to ordinary Portland concrete (OPC). The main difference is that foam concrete has a considerably lower weight because of the high amount of air bubbles within its matrix. As the voids determine the density and the strength of foam concrete, the most critical step in production is controlling the characteristics of the voids, such as their nature, size and distribution ²².

Foamed concrete has many advantages compared to normal concrete. The high flowability and light weight of foamed concretes have expanded their application to large scale construction projects worldwide such as filling grades, structural members, road embankment infill and prefab SIP²³, ^{24, 25}. The low cement content and high amount of air used in these concretes provide more economical and environmentally friendly building materials that considerably reduce the dead load of construction, as well as labour and operating costs ^{26, 27}. On the other hand, foamed concrete offers several operational benefits such as high fire resistance, and excellent thermal and acoustic insulation properties ^{23, 28, 29}. In the last decade, there have been significant advancements in foam concrete technologies. Many efforts have been devoted to investigating the characteristics of the foams and enabling large-scale usage of foam concretes in a wide range of structural applications ^{23, 26, 27, 30, 31, 32}. Various foaming agents have been utilised to improve the properties of fresh and hardened concrete ^{33, 34, 35, 36, 37, 38}. The main challenge in selecting the right type and amount of the foaming agent is the ability to maintain the stability of the voids according to ASTM C 869-91 test procedures ³⁹.

The quality and the amount of water, the impact of different foaming techniques, fibres and different concrete mix designs have been extensively studied to improve the properties of fresh and hardened foam concretes ^{18, 25, 27, 40, 41, 42, 43, 44}. Chemical admixtures and superplasticisers are also used to decrease the water to

cement ratio in foam concretes in order to improve their properties ^{25, 45, 46}. The main challenge associated with the selection and use of a chemical admixture is the compatibility of the chemicals with the foaming agents. Following BS EN 934-2 recommendation, there are restrictions on the amount and type of chemicals that can be used in foam concrete applications ^{45, 47}. ACI Committee 544 also recommends the use of fibres in foam concrete ⁴⁸. The other factors that need to be taken into account are the workability of the foam concrete and its curing condition, especially when different mix designs are used. The usual slump test used in normal concrete is not applicable for foam concrete because of its very high flowability. The spread of the foam is found to be a better indicator of the workability in foam concrete 49. Research has also been conducted into finding an optimum curing condition for foam concrete. ASTM C 796 suggested a curing procedure for lightweight and cellular concretes, namely three days of curing at 100% relative humidity followed by oven dry curing for 72 hours at 60 $^{\circ}$ C 50 . The difference between the dry and wet density of foam concrete after curing can be controlled to be within a 50-100 kg/m³ density range ⁵¹. The resulting foam concrete is expected to have drying shrinkage of about 0.1-0.35% of the total hardened volume of the concrete ⁵², and a sorptivity of about 4-8% according to ACI 213R 53. Foam concrete can absorb sound 10 times faster than normal concrete and for every 100 kg/m³ drop in density, their thermal insulation capacity increases by about 0.04 W/mK. Moreover, foam concrete with 950 kg/m³ density can show about 3.5 hours of fire resistance ^{54, 55}.

Recent significant fire events in high-rise buildings highlight the pressing need for fire resistant construction materials in the construction industry. Foam concretes can be a tangible solution to this problem. While foam concretes provide many benefits to the construction industry, they pose challenges with achieving a consistent manufacturing quality and predictable properties. The combination of physical, chemical and structural analysis of foam concrete is critical for understanding their properties and predicting their performance. In this paper, the new developments in characterising concrete foams and their applications for the prefabricated housing industry have been investigated and discussed. With the aid of advanced analysis techniques, the characteristics of foam concrete can be customised for specific construction applications. Also, a good understanding of the desirable properties and limitations in this domain opens up opportunities for utilising new materials in this field and converting land-fill wastes to high-value products.

2. CONCRETE FOAM AND FOAMING

There are two main methods to introduce voids in foam concrete. The first is using endogenous gas generation by adding chemical agents such as H₂O₂, Al or Zn powders as gas-releasing agents into the cement paste. The second method is introducing a large volume fraction of air bubbles into the concrete mix via a prefoaming method. The foaming agents of the prefoaming method are usually synthetic 56 or proteinbased surfactants 57. Regardless of the foaming technique, controlling the total porosity of foamed concrete and the homogeneity of the pore distribution are the keys to optimising many fundamental properties such as thermal performance and compressive strength. The recent advancement in designing and manipulating foam characteristics is presented and discussed here for both foaming techniques.

2.1. Controlling the foaming process

The stability of foam is determined by its lifetime, and this factor is influenced by the drainage of liquid films, densification and coalescence of bubbles. The collective effects and interactions of these processes create challenges with investigating foam stability ^{58,} ⁵⁹. In order to improve the stability of concrete foams, various techniques such as the addition of foam stabilisers (in combination with a surfactant or with chemical foaming) are adopted ^{59, 60}. The challenge is to obtain foams with sufficient stability to withstand the cement preparation process while controlling the resultant pore sizes, and producing predictable densities and optimum properties. Depending on the foaming method and the application of the concrete foam, an appropriate process can be implemented for controlling the characteristics of the foam.

2.1.1. Foamability and Foam stability

In the mechanical foaming method, foam is created by mixing water and surface active agents such as sodium dodecyl sulphate (SDS) at a certain proportion in advance to stabilise the foam and densify the Plateau borders. The pre-made foam is then mixed with the concrete slurry. After forming the cellular shapes, the concrete hardens under a specific temperature (ambient or oven cured) and pressure. This method is expected to obtain relatively controlled and uniformly distributed voids throughout the concrete mix with thin liquid Plateau borders surrounding the air voids. Hence, the density, strength and thermal conductivity of the concrete will be decreased.

Water plays an important role in the foam concrete. The composition of cementitious materials, workability requirements and filler type are all influenced by the quantity of water. To maintain certain workability, the water absorption ability of some lightweight fillers such as perlites needs to be taken into account when determining the required water content. Current research on foam concrete indicates a water to cement ratio (w/c) of 0.45-0.65, and if superplasticiser is not utilised, the w/c may even go up to 1.25^{23} .



Figure 4. The effect of water content on the pore size distribution in alkali-activated slag foams ⁶¹

During the mechanical mixing of concrete slurry and foam, the water content of the slurry is the key factor in the bubble breakage of the foams. The initial concentration of the foam will drop by increasing the water content of the mix designs. In sheared foam, occurs more bubble breakage with highly concentrated foams. This could lead to the rupture of liquid film around the bubbles and foam collapse. On the other hand, the foams with very high water content are prone to foam sorting (arrangement of the bubbles according to their size) during mixing and pouring into the moulds. Consequently, strength development and thermal conductivity of lightweight foams can be deteriorated as a result of the low homogeneity in the size distribution of voids (Figure 4).

2.1.2. Chemical foaming and mix design

Controlling the foaming process is more challenging in the chemical foaming method. Simultaneous reactions between the foaming agent and the cementitious materials bring some complexity in foam stability. In general, if the chemically stable environment for the foaming reaction coincides with the accelerated setting of the binders, this results in more homogenous distribution of the fine pores in the matrix. An uncontrolled chemical foaming reaction leads to more variations in the pore size and distribution, and reduces the circularity of the voids ⁶², ⁶³. Therefore, the mix design for the cement matrix can play a key role in controlling the foaming process to obtain a desirable morphology of the voids (Figure 5).

Figure 6 illustrates the morphology of different fly ash geopolymers foamed with aluminium powder. From these microscopic images, it can be observed that the size and shape of the voids are changing significantly between the samples with different mix designs. While the same amount of aluminium powder is added to all samples, the different mix designs of cementitious binders produce a variable chemical environment for the foaming reaction. Therefore, the accelerating and retarding impact of the chemical environment directly affects the extent of foaming, the final density of the matrix, and the size and morphology of the pores. The application of the foams defines whether their shape, size and connectivity are desirable. While the small size and homogeneity of the pores are known to be important for compressive strength and thermal insulation, it is more desirable to have less regular shapes for better acoustic performance since the irregularity of the voids assist with better wave dissipation within the matrix.



Figure 5. The effect of mix design on foam characteristics in geopolymer foams made with metakaolin and H₂O₂⁶³



Figure 6. Microscopic images of fly ash geopolymers foamed with aluminium powder. The increased aluminium reaction rate from sample a) to c) changes the size and morphology of the voids ⁶²

The combination of atomic force microscopy (AFM), in-situ Fourier transform infrared spectroscopy (FTIR) scanning electron and microscopy (SEM) studies revealed the role of aluminium in the early and later stages of the polymerisation process (Figure 7). It has been shown that aluminium precipitates as a hydroxide gel and has an important influence on the dissolution rate of fly ash, which impacts the extent of the fly ash contribution to the reaction and gel formation.



Figure 7. Topographic images of a) sample with Al and b) sample without Al over a 10 x 10 μ m surface area, and the corresponding map of elastic modulus data for c) sample with Al and d) sample without Al after two days ⁶⁴

2.2. Characterising the cellular structure

Due to the high degree of voids, foam concretes have good thermal insulation properties, which is beneficial to the energy efficiency of buildings. However, foam concrete is typically weaker with a compressive strength of 1-10 MPa for a density range of 360-1400 kg/m³. The modulus of elasticity of foam concrete is usually between 1.7 and 3.5 GPa ⁶⁵. All these properties are dependent on the filler type and fraction, water-cement ratio, void properties and the curing procedure. Furthermore, foam concretes have much higher shrinkage compared to ordinary concrete.

2.2.1. Pore size and homogeneity of pore distribution

Non-destructive techniques can be utilised to quantify the homogeneity of the pore size and distribution within foamed concrete. The Ultrasound Pulse Velocity (UPV) technique has been found useful for detecting dissimilarities in the pore distribution (Figure 8). This technique can be very useful when an inconsistency with the pore distribution is observed in foams. This inconsistency, which is usually referred to as 'foam layering' or 'bubble arrangement', is not desirable for thermal insulating foams. This is because the relative orientation and position of the pores have a more profound impact on heat transfer compared to the amount of pores. Cement foams with high water ratios and foams made with chemical foaming agents (without modifiers) are prone to this layering effect, and it will be very beneficial to monitor their consistency by non-destructive testing techniques.



Figure 8. Non-destructive testing technique to detect the inconsistency of pore distribution ⁶³

UPV is measured on foamed samples in various directions and the deviation among the collected data is used as an indication of the homogeneity of the pore distribution. These results have been validated by microscopic images taken from different layers of foamed concrete samples, which showed that the largest deviation was related to the most layered porosity (Figure 8).

2.2.2. 3D studies by micro-CT scan images

Micro-CT scanning of foam concrete has been proven to be useful to study various aspects of the foam characteristics. While it is a timely and relatively expensive test, the results can provide some unique information regarding different characteristics of the foams. By compiling many images that are taken within micrometers of each other, the 3D image of the matrix can be generated and elucidated. This is of high value for quantifying the foam characteristics such as the circularity percentage of the pores (Figure 9a), or the amount of aggregates distributed in foamed concretes (Figure 9b).



Figure 9. a) Quantifying the circularity of pores and b) monitoring the distribution of type crumbs within the cement foam ^{62, 66}

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This technique has been also found quite useful for coupling with finite element modelling to simulate the behaviour of foamed concrete samples under loading. The resulting model can be used to predict the performance of foam concrete with variations in porosity and pore characteristics. The accuracy of the simulation is contingent on the amount of information available on the pore characteristics. For example, the inclusion of the pore connectivity factor has been found to increase the accuracy of the compressive strength obtained from the simulation (Figure 10).





element model (DEM) under compression ⁶⁷

3. CONCLUSIONS

Despite many advantages of foamed concretes and the extensive research in this domain, the application of these attractive, lightweight materials in the prefabrication industry has not reached its true technological maturity. Due to the lack of control over the consistency and properties of the foams, the production of concrete foams within a predictable method is still challenging. Also, the standards and specifications for foam concretes are not fully developed. which leaves some discretionary approaches in different stages of their manufacturing process. In order to facilitate the application of foam concretes in various large-scale construction projects, there is a need for further fundamental advancements in this technology to lay the ground for the development of applicable standards, guidelines and testing procedures.

The recent significant fire events in high-rise buildings highlight the pressing need for developing fire-resistant sandwich panels, which can replace existing combustible panels. Concrete foam technology can be a solution for this application. Due to the lightweight characteristics of these panels, there is significant potential in utilising wastes and developing high-performance, lightweight structures. Through advancing the knowledge regarding the characteristics of foams and their interrelation with specific properties of the concrete, it is possible to provide the foundation required for large-scale developments in this technology.

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