Low Carbon Geopolymer Hollow Block—Mix Design, Casting and Strength Comparison with OPC Hollow Block

U. Johnson Alengaram, Iftekhair Ibnul Bashar, Marios Soutsos, Karthick Srinivas, Daniel Kong, Arreshvhina Narayanan, Ooi Jieun Lin, P. S. Khoo, Abhey Gupta and William Doherty

Abstract Cement masonry units are not considered as sustainable due to consumption of fuel, cement and natural resources and embracing alternatives is mandatory. Geopolymer is a green cementitious material and has excellent mechanical properties, consumes low energy in production and emits less carbon dioxide. The effects of paste volume, proportion of alkaline activator and water/solid ratio were investigated to develop self-standing dry mix of geopolymer hollow block and compared with OPC mix. Factors that require attention in casting geopolymer dry mix are discussed in this article. The optimized mix of geopolymer self-standing dry mix is expected to be found between 30 and 35% of geopolymer paste volume for 7.5% of alkaline dosage and alkaline molar ratio of 1.00.

Keywords Low carbon · Dry mix · Hollow masonry unit/block · Geopolymer · Failure pattern

U. J. Alengaram (✉) · I. I. Bashar · K. Srinivas
Centre for Innovative Construction Technology (CICT), Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
e-mail: johnson@um.edu.my

M. Soutsos
School of Natural and Built Environment, Queen's University, Belfast, UK

D. Kong
Monash University, Bandar Sunway, Malaysia

A. Narayanan · O. J. Lin
Sunway Paving Solutions Sdn Bhd, Bandar Sunway, Malaysia

P. S. Khoo
Ikhmas Jaya Group Berhad, Petaling Jaya, Malaysia

A. Gupta
Macrete (Ireland) Limited, Antrim, UK

W. Doherty
Creagh Concrete Products Limited, Antrim, UK

© Springer Nature Switzerland AG 2020

F. Mohamed Nazri (ed.), *Proceedings of AICCE'19*, Lecture Notes in Civil Engineering 53, https://doi.org/10.1007/978-3-030-32816-0_71

1 Introduction

The phrase "energy" is the one of the most widely debated topics in most of the national and international arenas due to rapid and significant depletion of the natural resources; this causes substantial adverse impact on global environment. By recycling and renewing materials and utilizing resources in a smart way, the burden on energy consumption can be reduced. Therefore, like every sector, building industries are also forced to practice green building technology. As a result of this concern, green building index is being encouraged to be implemented in every building in Malaysia and systematic regulation has been enforced by European commission for Europe.

The energy consumption by buildings and structures can be reduced by designing energy efficient building, adopting energy efficient building product and utilizing green raw material. The insulation performance of building wall significantly and directly affects the consumption level of energy [4]. The insulation performance of building wall can also be improved using hollow blocks [7]. Due to having hollow in hollow block, heat transfers through the wall reduces and thus energy saving is considerably increased compared to solid walls.

This research article is envisioned and focused on the development of low carbon block using geopolymer technology. There is an optimistic environmental impact in manufacturing low carbon geopolymer hollow block (GHB). Ordinary Portland cement (OPC) was replaced wholly by fly ash (FA) as binding material. There is difference in casting procedure for hollow block and conventional concrete. Dry mix is required for casting hollow block whereas wet mix is practical for conventional concrete. Due to be dry mixture, the ability of self-standing after immediate demolding is challenging; thus in order to determine an appropriate proportion of liquid, paste and fine particles is vital aspect of mix design. Particle packing method is one of the widely used methods for designing dry mix recipe. However, in geopolymer concrete, presence of silicious material makes the paste viscous; thus it is quite important to consider additional factor in dry mix for GHB. Hence the main objective of this research is to develop GHB considering appropriate proportion of activator, paste volume and casting techniques.

2 Methodology

Hollow blocks were cast using dry mixture of binding material, fine sand, coarse sand, granite chip and activators (in liquid form). Ordinary Portland Cement (OPC) and class F fly ash (FA) were used as binding materials in OPC hollow block (HB) and geopolymer hollow block (GHB), respectively. OPC was activated using water by hydration process whereas alkaline based activator was used to activate FA.

The mix design is shown in Table 1. The percentage of fine sand was varied among the mixes HB1–HB4 to achieve better surface finishing of HB. On contrary, the factors—alkaline dosages and paste volume were varied among mixes GHB1–GHB7 to achieve optimized quantity. The optimization of paste was determined based on self-standing capability of cast specimens immediately after demolding upon casting.

It should be noted that block industries provide hydraulic pressure and vibration and these factors contribute to the development of comparatively higher strength than the mixes cast in the laboratory for casting blocks. Dry mix (Fig. 1) was poured in block-making machine mold (Fig. 2) in two layers. The bottom plate and top end of mold (caging part) was vibrated for 5 s after pouring each layer; therefore, each specimen was vibrated for about 20 s under weight of top caging

Table 1 Mix designs for hollow blocks (HB and GHB)

Mix ID	Paste volume (%)	M+ (%, alkali dosage)	AM (alkali modulus)	w/s	Total aggregate volume, Ag_{total} (%)			Remarks
					Fine sand (% of Ag_{total})	Coarse sand (% of Ag_{total})	Aggregate chip (% of Ag_{total})	
Mix design for OPC hollow blocks								
HB1–HB4	23.00	–	–	0.45	77.0			
HB1					0.0	75.0	25.0	
HB2					10.0	65.0		
HB3					20.0	55.0		
HB4					30.0	45.0		
Mix design for geopolymer hollow blocks								
GHB1	35.27	9.66	1.00	0.20	64.7			[1]
					7.5	67.0	25.5	
GHB2	14.00	7.50	1.00	0.38	86.0			[2]
					7.5	67.0	25.5	
GHB3	20.00	7.50	1.00	0.38	80.0			
					7.5	67.0	25.5	
GHB4	22.55	5.54	1.00	0.29	77.5			[3]
					7.5	67.0	25.5	
GHB5	30.17	7.50	1.00	0.57	77.5			
					7.5	67.0	25.5	
GHB6	26.83	7.54	1.00	0.47	73.2			
					7.5	67.0	25.5	
GHB7	29.09	7.54	1.00	0.42	70.9			
					7.5	67.0	25.5	

[1] Below 35% volume of paste aggregate chip was found separated from the mortar mixes
[2] Mix could not be cast; all blocks were broken immediately after demolding
[3] Mix could be cast and demolded immediately after casting

Fig. 1 Dry mix of geopolymer hollow block

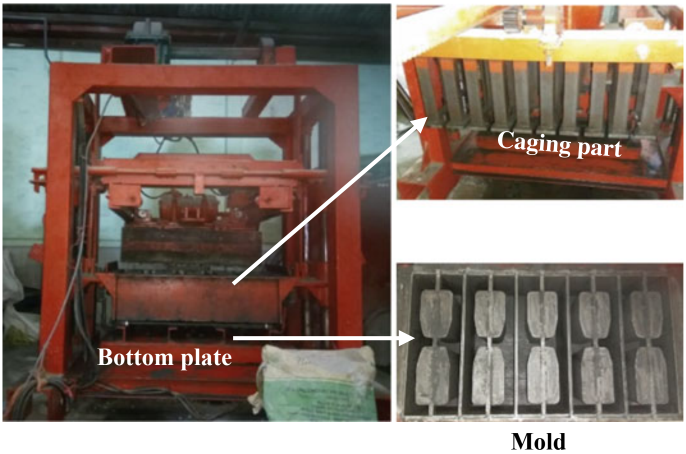


Fig. 2 Block making machine and molds

part of block making machine. The vibration time limit was calibrated by several trial castings to achieve appropriate compaction in block molds for getting self-standing specimen after immediate-demolding of casting.

The estimated pressure due to caging part weight on specimen during vibration was about 0.04 N/mm^2 which is negligible compared to the hydraulic pressure generally provided in industry during block manufacturing. Figure 3 shows the dimensions of the block specimens. Hollow blocks specimens were prepared in accordance with ASTM C90–14 and the compression test was carried out following ASTM C652 (2011) (Fig. 4).

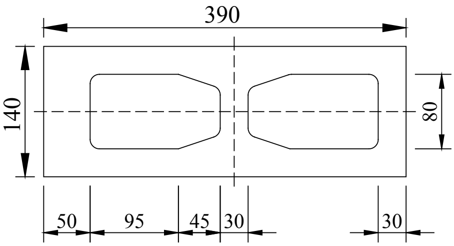
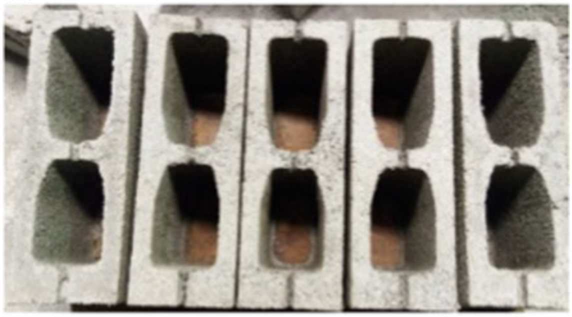


Fig. 3 Dimensions (mm) of hollow blocks (height 200 mm); gross area = 54,600 mm^2; net area = 28,523 mm^2

(a)



(b)

Fig. 4 **a** OPC hollow block, **b** geopolymer hollow block

3 Result and Discussion

3.1 Factors to be Considered in Mix Design and Casting of Geopolymer Hollow Blocks

Casting of geopolymer hollow block using block making machine requires dry mixture. The challenging factor in dry mix design is to adopt appropriate quantity of liquid activator for self-standing block specimen for immediate demolding after casting without compromising precursor-activation-rate and binder strength. Therefore, adopting optimized water/solid ratio and alkaline dosage for precursor activation is very important in the first stage of mix design. Then the volume of paste should be optimized to get the self-standing specimen.

It was found among the mix designs as shown in Table 1 that below 35% paste volume, the aggregate chips were separated from the mortar. Though in some cases of mixes GHB4–GHB7, it was noticed that the specimens were able to self-stand immediately after demolding (Figs. 7, 8 and 9), however, due to separation of aggregate chip, the homogeneity was uncertain; this would in turn affect the particle packing in concrete matrix; ultimately this would affect the strength development [3]. It is impossible to cast specimen using 20 and 14% paste volume. Figure 6 shows the collapse of GHB2 (14% paste) and similar failure was noticed for GHB3 (20% paste) too, due to dryness of the mixture. Figure 5 shows that the mix-GHB1 which was considered as dry-mix (35% paste) could be promoted for self-standing hollow block casting.

The selection of mixer machine is significant in order to produce a homogeneous mixture. And its significance in geopolymer casting could be more compared to OPC concrete due to viscous property of geopolymer. The geopolymer mix with less water/solid ratio forms round or spherical particles of small to large sizes in

(a) self-standing blocks immediately after cast (b) good surface finishing.

Fig. 5 Casting of GHB1

Fig. 6 Collapse of GHB2

Fig. 7 Self-standing GHB4 before oven curing—immediately after casting

Fig. 8 Surface finishing of GHB4

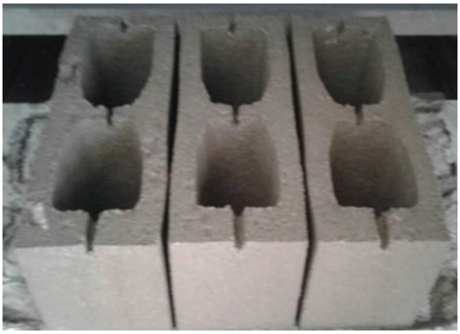


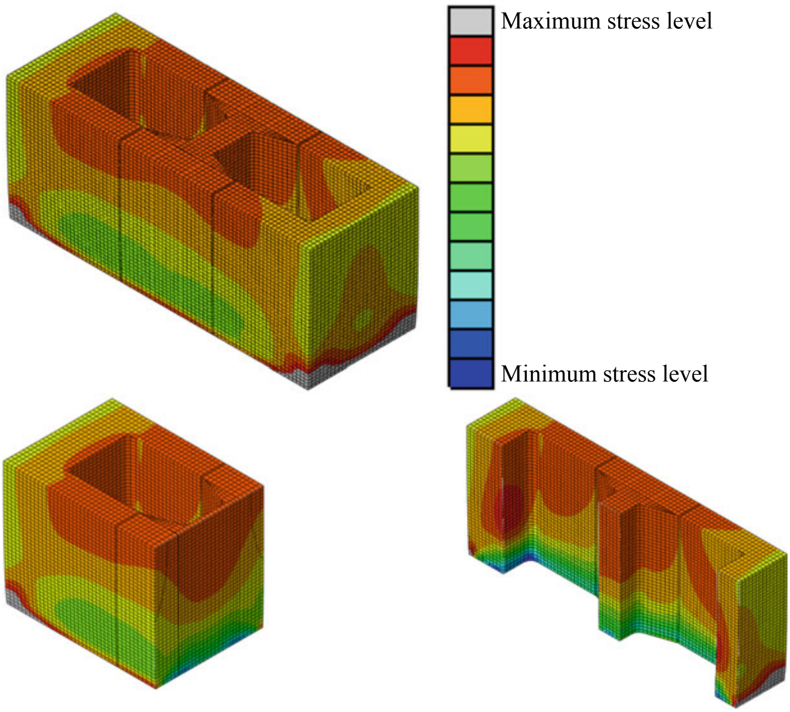
Fig. 9 Surface finishing of GHB7

rotary mixer machine; this could be attributed to centrifugal motion as shown in Fig. 1. Similar formation of geopolymer concrete balls was also reported by Bashar et al. [2]. The homogeneity of paste and aggregate proportion might be affected due to this reason. A laterally rotated pan mixer is considered as better option for less water/solid ratio based geopolymer mixture to avoid formation of round or spherical shapes during mixing that would normally occur in rotary mixer.

Since low Calcium FA was used, curing of the GHB specimens in oven is mandatory. To avoid any micro-crack generation, it is imperative to leave the specimens at casting yard for few hours before moving to the curing chamber for curing at 70 °C for 24 h in order for the specimens to achieve the desired strength.

3.2 Failure Mechanism in Compression

In a solid cube, the compression stress disseminates from the center portion of the cube toward edges. In hollow block, stress distribution though starts from the center of loading plane, depending on the shape and position of the hollow, stress distribution takes place as shown in Fig. 10. The failure occurs due to shear sliding between two different layers of stresses.



(a) Cut section at mid along long dimension (b) Cut section at mid along short dimension

Fig. 10 Stress distribution in hollow block under compression

Fig. 11 Failure patterns of OPC hollow blocks

The crack patterns as shown in Figs. 11 and 12, are comparable with the stress distribution path in Fig. 10. However, due to be less ductility of geopolymer compared to OPC hollow block, the debris from the broken portion of the GHB were found looser than HB (Fig. 12a, b). Based on failure pattern, GHB7 was found more stable than GHB1. Higher w/s ratio of GHB7 compared to the mix-GHB1 attributes to increasing packing ability. Further owing to higher water quantity, the mix-GHB7 was found to have smoother surface compared to the mix-GHB1.

3.3 Compressive Strength—Comparison Between Geopolymer and OPC Hollow Block

The highest compressive strength among HB1–HB4 mixes was found for HB1 (Table 2) which contained zero percentage of fine sand. Since the paste volume was kept constant for HB1–HB4, the demand of paste was increased due to replacement of coarse sand by fine sand as the surface area was increased [1]. Though the replacement of coarse sand by fine sand enhances the packability, the strength could not be increased in dry mix.

Among GHB1–GHB7 mixes, the highest compressive strength was achieved by GHB1 due to presence of high volume of paste (Table 2) and higher dosage of alkaline activator. GHB7 was adopted as optimized alkaline dosage with 7.5% [5] and higher water/solid ratio than GHB1. This could be considered as the factor to compensate the strength comparably. Further, an increase of water/solid ratio had adverse result in strength development as found for mixes of GHB5 and GHB6.

It should be noted that the pressure applied on the blocks during casting was much lower than that is being applied in industry. Due to poor compaction, the strength obtained was found lower. Applying higher compaction pressure during casting, particle packing will be increased that would be crucial in the enhancement of strength [6].

Fig. 12 Failure patterns of geopolymer hollow blocks

Table 2 Compressive strength (MPa) tested in pace rate of 3.70 kN/s

	HB1	HB2	HB3	HB4	GHB1	GHB4	GHB5	GHB6	GHB7
Gross	5.8	4.2	4.2	4.1	4.0	0.5	2.0	2.3	3.2
Net	11.1	8.0	8.0	7.8	7.7	1.0	3.8	4.4	6.0

3.4 Applicability of Technology and Application of Developed Hollow Block

The technology of developing GHB is considered vital in spearheading low carbon building block manufacturing. Due to usage of zero cement and whole replacement of conventional material using industrial by-product pozzolan (FA) as binding material, about 30% of raw material would result in reduction of CO_2 emission. The developed hollow blocks will be suitable for indoor and outdoor applications in building premises and partition walls.

3.5 Real Time Implementation of the Developed Technology

This technology which incorporates the usage of zero cement and whole replacement of conventional materials using industrial by-product pozzolan (FA) as binding material is to be implemented in the real scale as a demonstration and publicity project—Impact and dissemination under the research grant Newton-Ungku Omar coordination fund on low carbon footprint precast concrete products for an energy efficient built environment; two projects are planned and those are in the final stages of production phase and soon these two projects will become reality for the public to witness the cement less structures in Malaysia. The projects include construction of flexi-arch bridge in the University of Malaya campus (Fig. 13a) as well as construction of prototype cement less housing located at Sunway, Batang Kali, Selangor, Malaysia (Fig. 13b); the materials that would be used in these projects comprise of high-value, low-carbon cement less precast concrete structure which simultaneously addresses the challenges of both Future Cities and Improving Environmental Resilience and Energy Security of the competition. Demonstration of the flexi-arch bridge will confirm that cement less concrete as cost competitive to OPC concrete (Fig. 13a); similarly, the construction of prototype cement less housing at Sunway, Batang Kali, Selangor, Malaysia would be another testament to the use of alternate materials to cement in concrete in Malaysia.

The LowCoPreCon brings together a consortium of seven partners in a UK-Malaysia Innovation Bridge. QUB, specialist precast concrete products companies Creagh Concrete Products Ltd. (CCP) and Macrete (Ireland) Ltd. in the UK. In the Malaysia participation comes from the Centre for Innovative Construction Technology (CICT), Department of Civil Engineering at the University of Malaya

Fig. 13 **a** Location and preliminary drawing of Flexi-arch bridge to be constructed at University of Malaya, Kuala Lumpur, Malaysia, **b** location and preliminary drawing of demonstration dwelling to be constructed at Sunway, Batang Kali, Selangor, Malaysia

(UoM), the School of Engineering at Monash University (MU), building products company Sunway Paving Solutions (SPS), and construction company Ikhmas Jaya Group Berhad (IJGB).

4 Conclusions

Based on the research discussed in this article, the following may be summarized: The optimization of geopolymer paste volume was found between 30 and 35% using optimized quantity of activators; thus, the optimized alkaline dosage and alkaline molar were found to be 7.5% and 1.0, respectively. The compression stress based on net area was achieved 7.7 MPa for 35% of paste volume; however, this strength may not reflect the factory method of development of HB as the usage of hydraulic pressure during casting would certainly enhance the strength. Laterally rotated pan mixer is more appropriate for mixing geopolymer dry mixer. GHB may be applicable for indoor and outdoor of building wall for residential building.

Acknowledgements The authors gratefully acknowledge the financial support under the research grant Newton-Ungku Omar coordination fund IF007-2017: Low carbon footprint precast concrete products for an energy efficient built environment.

References

1. Bashar II, Alengaram UJ, Jumaat MZ, Islam A (2014) The effect of variation of molarity of alkali activator and fine aggregate content on the compressive strength of the fly ash: palm oil fuel ash based geopolymer mortar. Adv Mater Sci Eng
2. Bashar II, Alengaram UJ, Jumaat MZ, Islam A, Santhi H, Sharmin A (2016) Engineering properties and fracture behaviour of high volume palm oil fuel ash based fibre reinforced geopolymer concrete. Constr Build Mater 111:286–297. https://doi.org/10.1016/j.conbuildmat.2016.02.022
3. Hettiarachchi H, Mampearachchi W (2019) Validity of aggregate packing models in mixture design of interlocking concrete block pavers (ICBP). Road Mater Pavement Des 20(2):462–474
4. Mohsen MS, Akash BA (2001) Some prospects of energy savings in buildings. Energy Convers Manag 42(11):1307–1315
5. Soutsos M, Boyle AP, Vinai R, Hadjierakleous A, Barnett SJ (2016) Factors influencing the compressive strength of fly ash based geopolymers. Constr Build Mater 110:355–368
6. Wattanasiriwech D, Saiton A, Wattanasiriwech S (2009) Paving blocks from ceramic tile production waste. J Clean Prod 17(18):1663–1668
7. Yu J, Yang J, Xiong C (2015) Study of dynamic thermal performance of hollow block ventilated wall. Renew Energy 84:145–151. https://doi.org/10.1016/j.renene.2015.07.020