EASR

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

Behavior of concrete cylinders confined by a ferro-geopolymer jacket in axial compression

Kothay Heng[1, 2], Natthapong Areemit[2] and Prinya Chindaprasirt[*2]

[1]CJEC Engineering & Construction Co., Ltd, Sangkat Phnom Penh Thmey, Khan Sen Sok, Phnom Penh, Cambodia
[2]Sustainable Infrastructure Research and Development Center, Department of Civil Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand

Received September 2016
Accepted October 2016

Abstract

It is beneficial to utilize geopolymers for their potential properties to rehabilitate concrete structures. These properties include high adhesion to Ordinary Portland Cement (OPC) concrete even at low degrees of interfacial roughness, high durability and good fire resistance. This paper introduces use of a ferro-geopolymer jacket to strengthen concrete columns. It is a kind of jacket constructed with a geopolymer mortar reinforced with a wire mesh. This study was conducted to investigate the behavior of concrete cylinders confined with a ferro-geopolymer jacket in axial compression. OPC concrete cylinders with 100 mm diameter and 200 mm height were fabricated. High calcium fly ash-based geopolymer mortar, activated with sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), cured at a temperature of 25 ºC was used. Ferro-geopolymer jackets with a25 mm thickness, were reinforced with 1, 2 and 3 layers of expanded metal mesh and cast around concrete cylinders. The study results revealed that the compressive load carrying capacity and axial stiffness of concrete cylinders were improved. A monolithic failure mode was obtained as a result of a strong adhesion between the geopolymer and the concrete core. Enhancement of compressive load carrying capacity of the jacketed concrete cylinders was caused by a combination of a confinement effect and the compressive load resistance of the jacket transferred from concrete core through bonding.

Keywords: Ferro-geopolymer jacket, Compressive strength, Axial stiffness, Monolithic failure mode

1. Introduction

Rehabilitation of concrete structures is crucial to extend their service life in the face of chemical attacks in aggressive environments, overloading or exposure to extreme temperatures. Repair and strengthening of concrete columns is usually done by constructing external jackets to provide additional lateral confinement to enhance strength, stiffness and ductility [1-3].

Geopolymer is a material that is strongly adhesive to OPC concrete even at low degrees of interfacial roughness, comparable to commercial repair materials [4-5]. Moreover, geopolymer possesses high durability and good fire resistance [6-8]. For this reason, geopolymers are potential materials for rehabilitation of concrete structures [9]. Some research has been conducted using geopolymers as protective coatings for concrete, such as for concrete in marine environments[10] and for concrete sewage pipes[11].

In this study, a ferro-geopolymer jacket that consisted of a geopolymer mortar jacket reinforced with a wire mesh, was used to strengthen concrete columns. This research was conducted to investigate the behavior of concrete cylinders confined with a ferro-geopolymer jacket in axial compression.

2. Materials and methodology

2.1. Experimental design

The experiment was conducted on 20 concrete cylinders. OPC concrete cylinders that were 100 mm diameter and 200 mm height were used. Ferro-geopolymer jackets with a 25 mm thickness, reinforced with 1, 2 and 3 layers of wire mesh were cast around concrete cylinders. As shown in Table 1, the specimens were divided into four series (5 replicates per series). To prevent the jackets from direct compressive loads, 10 mm gaps were kept at the top and bottom of the jacket (see Figure 1). The OPC concrete was designed to have 28 days compressive strength of 20 MPa.

2.2. Materials

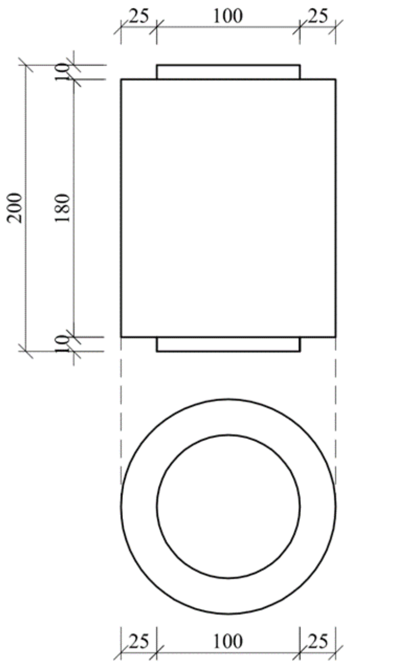
2.2.1. Aggregate

Crushed limestone with a maximum size of 19 mm was used as a coarse aggregate to make concrete. River sand with a fineness modulus of 2.55 was used to make both concrete and a geopolymer mortar. Both coarse and fine aggregates satisfied the grading requirements of ASTM C33 [12].

*Corresponding author.
Email address: prinya@kku.ac.th
doi: 10.14456/easr.2017.13

Table 1 Series of specimens

Series	Designation	Description
1	NJ	Non-jacketed specimens
2	J1	Jacketed specimens with 1 layer of wire mesh
3	J2	Jacketed specimens with 2 layers of wire mesh
4	J3	Jacketed specimens with 3 layers of wire mesh



Note: All dimensions are in millimeters

Figure 1 Geometry of specimens

Saturated Surface Dry condition (SSD) of the aggregate was prepared to prevent from absorbing water from the paste.

2.2.2. Cement and fly ash

OPC with a specific gravity of 3.15 was used to produce concrete cylinders. High calcium fly ash with a specific gravity of 2.41 from the Mae Moh Power Plant in Northern Thailand was employed to make the geopolymer. The chemical composition of fly ash was 35.9% SiO_2, 17.3% Fe_2O_3, 17.2% CaO and 15.1% Al_2O_3.

2.2.3. Alkaline solutions

Sodium hydroxide and sodium silicate solutions were employed to produce the geopolymer. Sodium silicate was comprised of 12.5% Na_2O, 30.2% SiO_2 and 57.2% H_2O. Preparation of sodium hydroxide was done by dissolving sodium hydroxide flakes in deionized water at least 24 hours prior to use.

2.2.4. Wire mesh

Through trial testing, it was revealed that galvanized wire mesh could not be used to reinforce geopolymers because sodium hydroxide reacted with zinc forming hydrogen gas. This created gas bubbles and resulted in expansion of the geopolymer mortar (see Figure 2).

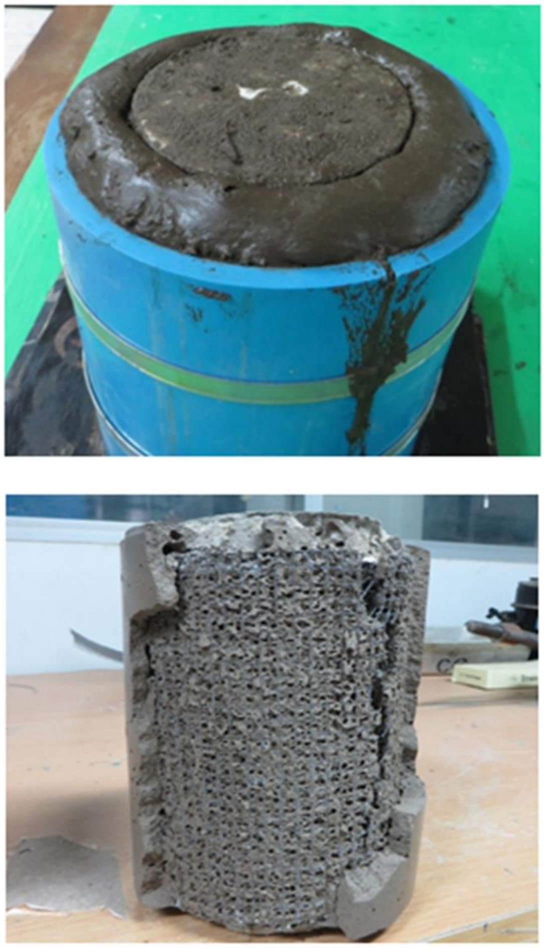


Figure 2 Expansion and formation of gas bubbles of geopolymer mortar when galvanized wire mesh was used

Non-galvanized expanded metal mesh was used as a mesh reinforcement of the ferro-geopolymer jacket (Figure 3). The unit weight of the wire mesh was 0.942 kg/m^2. Ultimate tensile strength of the expanded metal mesh was 378 MPa. According to ACI 549.1R-93 [13], the effective modulus of elasticity of the expanded metal mesh in the longitudinal direction was 138 GPa, and 69 GPa in the transverse direction. The expanded metal mesh had diamond-shaped holes with dimensions as follows:

- Long dimension of mesh: LW = 14.00 mm
- Short dimension of mesh: SW = 6.34 mm
- Width of strands: W = 0.42 mm
- Thickness of strands: T = 0.84 mm
- The strands were oriented 24º to longitudinal direction

2.3. Mix constituents

2.3.1. OPC concrete

OPC concrete with a compressivestrength at 28 days of 20 MPa was designed according to ACI 211.1 [14]. Its constituents were 297 kg/m3 cement, 205 kg/m3 water (W/C 0.69), 960 kg/m3 coarse aggregate and 843 kg/m3 sand.

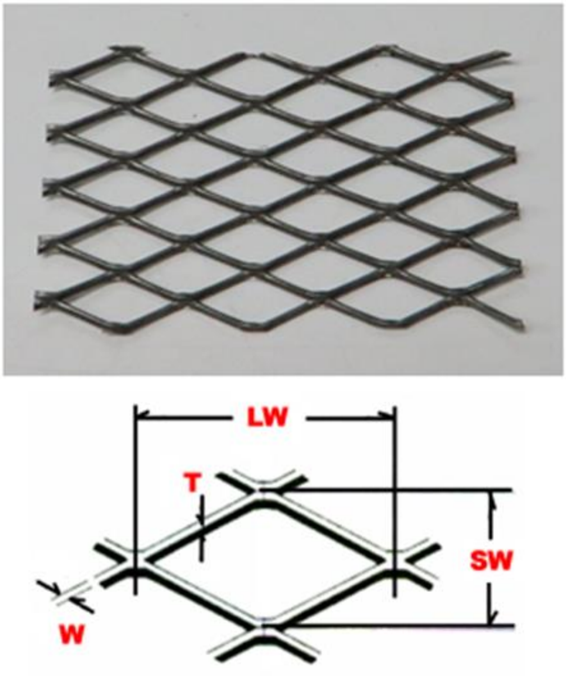


Figure 3 Non-galvanized expanded metal mesh

2.3.2. Geopolymer mortar

Mix proportions of geopolymer were adopted from the optimum mix in the research of Phoo-ngernkham et al. [5]. The sand to fly ash ratio was 1.5, so that the mortar was flowable with a measured flow of 105%. Sand that passed a No. 16 (1.18 mm) sieve was used to make the geopolymer mortar. The mix proportions of geopolymer mortar for the jacket are shown in Table 2. Compressive strength at 28 days of the geopolymer mortar was 37.63 MPa.

Based on the empirical equation relating the modulus of elasticity and compressive strength of the geopolymer mortar from the study of Phoo-ngernkham[15], the modulus of elasticity of geopolymer mortar at 28 days was estimated to be 10.66 GPa (Equation 1):

$$E = 4.12\sqrt{f`_c} - 14.613 \text{ (in GPa)} \quad \text{Eq.1}$$

Table 2 Mix constituents of geopolymer mortar

Fly ash (g)	Sodium hydroxide 14M (g)	Sodium silicate (g)	Sand (g)
100	20	40	150

2.4. Tensile strength of ferro-geopolymer jacket

Tensile strength testing of the ferro-geopolymer jacket was performed using rectangular specimens designed according to ACI 549.1R-93 [13]. The size of the specimens is shown in Figure 4. Ultimate tensile strength of the ferro-geopolymer reinforced with 1, 2 and 3 layers of wire mesh is shown in Table 3. CV represents the coefficient of variation.

2.5. Preparation of specimens

Making and curing of concrete cylinders were performed according to ASTM C192 [16]. After 28 days of curing in water, the concrete cylinders were prepared for ferro-geopolymer jacketing.

The concrete cylinder surfaces were roughened with a steel brush to remove grease and laitance as well as to improve interfacial roughness. Later, they were cleaned with water to remove dust and small particles. Before jacketing, concrete cylinders were prepared so that they were internally saturated with a dry interface by placing them in water for 24 h and drying them in air to prevent them from absorbing water from the geopolymer mortar. Then, the concrete cylinders were wrapped with an expanded metal mesh with the longitudinal direction of the wire mesh parallel to the direction of hoop tension (Figure 5). For J2 and J3 specimens, wrapping was done using 2 and 3 pieces of expanded metal mesh respectively. A 150 mm overlap of wire mesh was provided to prevent debonding of the reinforcement. The value of 150 mm was determined based on the minimum value of 100 mm for overlap length of wire mesh for ferrocement suggested by Kaushik et al. [17].through trial tests, it was found that there was no problem of debonding of the wire mesh when a 150 mm overlap length was used. Temporary spacing rods of 1.5 mm diameter were kept between the interface and first layer of wire mesh to provide a space for infiltration of geopolymer mortar.PVC pipes were used as molds for casting the jacket.

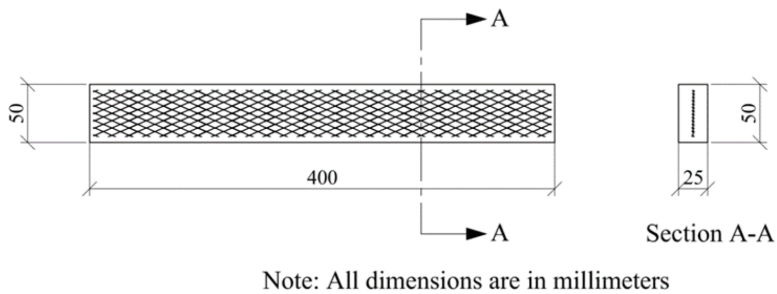


Figure 4 Overlay of an expanded metal mesh of ferro-geopolymer plates

Table 3 Tensile strength of ferro-geopolymer reinforced with 1, 2 and 3 layers of wire mesh

Number of layers of wire mesh	Ultimate tensile strength (MPa)				
	Measured			Average	CV (%)
1	1.16	1.11	1.24	1.17	5.60
2	2.10	2.14	2.25	2.16	3.59
3	3.79	3.89	3.76	3.81	1.79

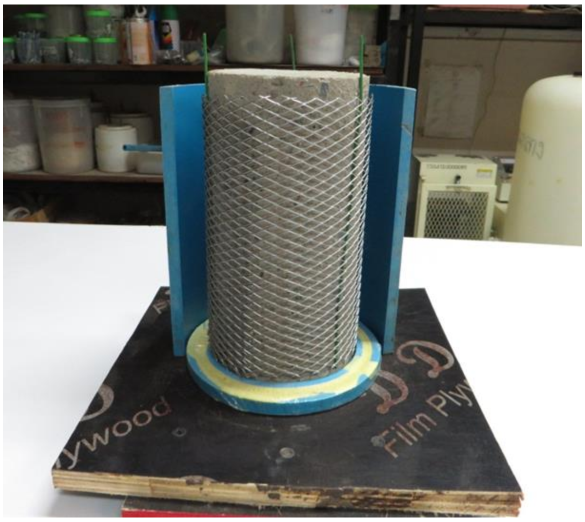


Figure 5 Specimens wrapped with expanded metal mesh

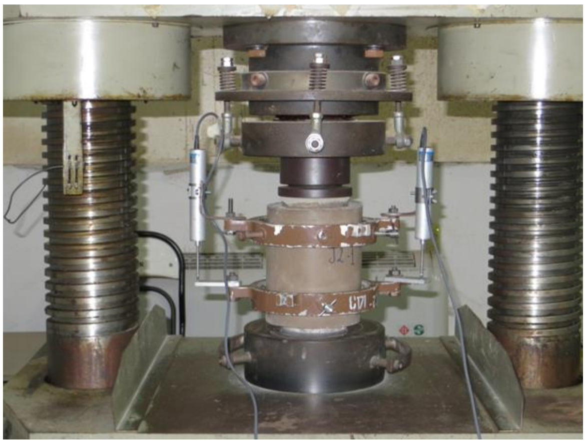


Figure 6 Jacketed concrete cylinders under compression testing

Next, the geopolymer mortar was mixed. Mixing was performed by initially blending sand and fly ash for 2 min. After that, the sodium hydroxide solution was added to the mixture and mixing was continued for another 5 min, followed by addition of a sodium silicate solution. Final mixing was done for 5 min [5].

Then, the geopolymer mortar was placed into the molds. Consolidation of geopolymer mortar was carried out by placing the specimens on a vibrating table and vibrating for 30 s. After 24 h, the specimens were demolded and wrapped in vinyl sheets to protect against moisture loss. The specimens were cured in a temperature controlled room at 25 ºC for 28 days. They were also wrapped in vinyl sheets and transferred to the temperature controlled room at 25 ºC and 50% R.H. for 28 days to provide the same conditions of hydration of concrete for non-jacketed specimens.

2.6. Instrumentation and testing procedures

The specimens were capped with cement mortar to provide a smooth loading surface. A water to cement ratio of 0.43 of the mortar was used with a sand to cement ratio of 1. Sand passing a sieve No. 16 was used.

The specimens were tested under axial compression with SHIMADZU Compression Testing Machine, model CCH3000-kNA of 3000 kN capacity. KYOWA LVDTs, model DTH-A-50, were used to monitor the axial deformation of the specimens. As shown in Figure 6, two LVDTs (100 mm gauge length) were installed on opposite sides of the sample in the vertical direction at the middle of the specimens.

Prior to testing, the compression testing machine and LVDTs were connected to a data logger to record load and axial deformation of the specimens. The KYOWA Data Logger, model UCAM-60B was used. The tests were performed with an axially compressive load at a 0.5 mm/min loading rate.

3. Results and discussion

3.1. Load-deformation responses of concrete cylinders

Load-deformation responses of NJ, J1, J2 and J3 are shown in Figure 7. The softening part of the load-deformation curves could not be obtained because after the compressive load reached its peak, cracks in the jacket caused the compressometer to slip. It was illustrated that axial stiffness of the jacketed specimens slightly increased compared to the non-jacketed specimens. It was also observed that, axial stiffness of NJ slightly decreased prior to the peak, while J1 and J2 maintained their axial stiffness.

The load carrying capacity of jacketed specimens was remarkably higher than for the non-jacketed ones. The ultimate compressive loads carried by the specimens are shown in Table 4.

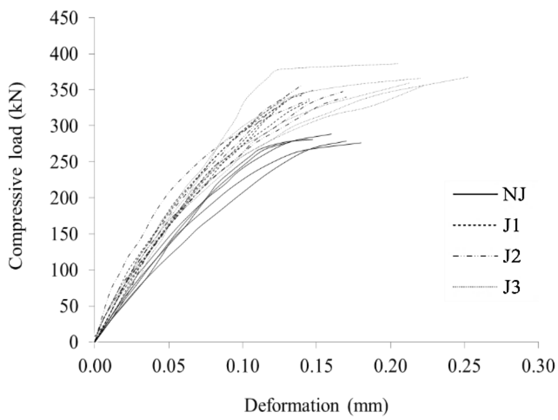


Figure 7 Plot of compressive stress versus axial strain of NJ, J1, J2 and J3

3.2. Failure mode of jacketed concrete cylinders

When the specimens were loaded, the lateral expansion of the concrete cores caused hoop tension in the jacket due to Poisson's effect. Thus, it resulted in expansion and cracking of the ferro-geopolymer jacket. First, a fine vertical crack was visible on the jacket when the compressive load reached 90-95% of its peak, followed by formation of other fine vertical cracks on various parts of the jacket.

After the compressive load reached its peak, the crack widths increased rapidly. The load carrying capacity of NJ dropped dramatically. For J1, J2 and J3, their load carrying capacities decreased gradually. Failure of the specimens was noticed when the wire mesh tore. At this time, large cracks were observed on the jackets and a sudden drop of the load carrying capacity took place (Figures 8 and 9). This was consistent with the failure mode of concrete cylinders confined with a square welded wire mesh ferrocement jacket.

Table 4 Ultimate compressive load carried by NJ, J1, J2 and J3

Specimens	Ultimate compressive load (kN)						
	Measured					Average	CV (%)
NJ	280.9	276.4	277.9	288.6	278.9	280.6	1.70
J1	316.6	334.8	341.7	341.6	330.7	333.1	3.10
J2	337.8	349.3	347.4	357.0	339.6	346.2	2.25
J3	365.7	386.0	367.6	355.8	358.9	366.8	3.20

Kaish et al. [2] found that the failure of the jacketed concrete cylinders occurred as a result of the failure of the wire mesh. Compressive loads at the time of failure of the specimens were 18-40% of the peak loads for NJ, 21-54% of the peak load for J1, 74-83% of the peak load for J2 and 81-89% of the peak load for J3.

It was observed that all the specimens failed monolithically. There was no disintegration between the jacket and concrete core as a result of strong adhesion between ferro-geopolymer jacket and concrete core (Figure 9). In contrast to ferro-geopolymer jacket, Kaish et al. [2] observed catastrophic failure of a single layer weld wire mesh ferrocement due to disintegration of the bond between the jacket and the concrete core, which could have been due to the low bonding strength between the OPC concrete and ferrocement jacket.

Figure 8 Tearing of the expanded metal mesh

Figure 9 Failed J1, J2 and J3 specimens (left to right)

3.3. Improvement in compressive load carrying capacity

The confinement model of concrete confined with a transverse reinforcement proposed by Mander et al. [18] could not be applied to design concrete columns strengthened with a ferro-geopolymer jacket. The enhancement in compressive load carrying capacity of ferro-geopolymer jacketed columns was contributed by two factors:

- Increased compressive strength of concrete due to confinement provided by the jacket
- The compressive load resistance by the jacket, which was transferred to the concrete core through bonding.

A mathematical model was established to estimate the contribution of improvement in compressive load carrying capacity of the jacketed concrete cylinders provided by the confinement effect and by the compressive load carried by jacket. The ultimate compressive load carried by the concrete cylinders jacketed with a ferro-geopolymer is expressed by Equation 2. The term $f`_{co}A_c$ represents the ultimate compressive load carried by non-jacketed concrete cylinders, the term $k.f_rA_c$ represents the compressive load carrying capacity enhancement due to the confinement provided by the jacket, and the term P_j represents the compressive load carrying capacity enhancement due to the compressive load resistance by the jacket transferred from concrete core through the bonding:

$$P = f`_{cc}A_c + P_j = (f`_{co} + k.f_r)A_c + P_j \quad \text{Eq.2}$$

where: P = ultimate compressive load carried by jacketed concrete cylinders (in N)
$f`_{cc}$ = compressive strength of confined concrete (in MPa)
A_c = cross-sectional area of concrete core (in m^2)
P_j = compressive load carried by the jacket (in N)
$f`_{co}$ = compressive strength of unconfined concrete (in MPa)
k = coefficient of confinement effectiveness
f_r = confinement stress (in MPa)

The confinement stress was calculated using Equation 3 [19].

$$f_r = \frac{2t}{D} f_{j\theta} \quad \text{Eq. 3}$$

where: t = thickness of the jacket (in mm)
D = diameter of concrete cylinders (in mm)
$f_{j\theta}$ = circumferential stress in the jacket (in MPa)

There were some limitations in this experiment. The circumferential strain and stress-strain relationship of the ferro-geopolymer were not measured. So, it was assumed that at the ultimate compressive load, the circumferential stress in the jacket reached its ultimate tensile strength.

Since differences among compressive loads carried by the jackets of J1, J2 and J3 were marginal and based on Equation 2, the change in the ultimate compressive load carried by the jacketed concrete cylinders was due to the change in confinement stress. So, the following equation can be obtained:

Table5 Coefficient of confinement effectiveness

Specimens	P (kN)	f_r(MPa)	ΔP(kN)	Δf_r(MPa)	k
J1	333.08	0.59	-	-	-
J2	346.22	1.08	13.13*	0.49*	3.41*
J3	366.81	1.91	20.59**	0.83**	3.15**

Note: *, ** The values were obtained from the differences between J2 and J1; and J3 and J2

Table6 Compressive load carrying capacity enhancement provided by the confinement effect and by the compressive load carried by the jacket

Specimens	P (kN)		f_r (MPa)	K_{ave}	$k.f_r.A_c$ (kN)	P_j (kN)
		Improvement				
NJ	280.55	-	-	-	-	-
J1	333.08	52.53	0.59	3.28	15.19	37.34
J2	346.22	65.67	1.08	3.28	27.82	37.85
J3	366.81	86.26	1.91	3.28	49.20	37.06

$$\Delta P = k.\Delta f_r.A_c \qquad \text{Eq.4}$$

where: ΔP = increment of ultimate compressive load carried by jacketed concrete cylinders (in N)

Δf_r = increment of confinement stress (in MPa)

Equation 4 was used to evaluate the confinement effectiveness coefficient. As shown in Table 5, the confinement effectiveness coefficients were found to be 3.41 and 3.15. Richart et al. [20] revealed that the value of k was 4.1 for concrete cylindrical columns confined with spiral reinforcement. Lam and Teng found the value of k was 3.3 for concrete cylinders confined with FRP jacket [21].

The average value of the confinement effectiveness coefficient was 3.28. This value was used to calculate the compressive load carrying capacity enhancement provided by the confinement effect. As shown in Table 6, the compressive load carrying capacity enhancement provided by the confinement effect was 15.19, 27.82 and 49.20 kN for J1, J2 and J3, respectively.

The enhancement in compressive load carrying capacity that was contributed by the compressive load resistance of the jacket was calculated by subtracting the total improvement in compressive load carrying capacity from that contributed by the confinement effect. As shown in Table 6, the enhancement in compressive load carrying capacity due to the compressive load resistance by the jacket was about 37 kN.

4. Conclusions

In this study, the behavior of ferro-geopolymer jacketed concrete cylinders in axial compressive loading was investigated. Based on our experimental results, it can be concluded that:

1. The compressive load carrying capacity and axial stiffness of jacketed concrete cylinders were improved.

2. Monolithic failure mode was obtained as a result of a strong adhesion between the geopolymer and OPC concrete core.

3. Enhancement in compressive load carrying capacity of the jacketed concrete cylinders resulted from a combination of the confinement effect and compressive load resistance by the jacket transferred from the concrete core through bonding.

5. Acknowledgements

This work was financially supported by the Sustainable Infrastructure Research and Development Center (SIRDC), Faculty of Engineering, Khon Kaen University and the Royal Scholarship under Her Royal Highness Princess Maha Chakri Sirindhorn Education Project to the Kingdom of Cambodia.

6. References

[1] Hongsinlark N, Boonpichetvong M, Pannachet T. Finite element modeling of axially loaded concrete columns with metal sheet confinement. KKU Eng J. 2014;41(4):517-25. [In Thai].

[2] Kaish ABMA, Jamil M, Raman SN, Zain MFM. Axial behavior of ferrocement confined cylindrical concrete specimens with different sizes. Constr Build Mater. 2015;78:50-9.

[3] Mourad SM, Shannag MJ. Repair and strengthening of reinforced concrete square columns using ferrocement jackets. Cem Concr Compos. 2012;34:288-94.

[4] Pacheco-Torgal F, Castro-Gomes JP, Jalali S. Adhesion characterization of tungsten mine waste geopolymeric binder. Influence of OPC concrete substrate surface treatment. Constr Build Mater. 2006;22(3):154-61.

[5] Phoo-ngernkham T, Sata V, Hanjitsuwan S, Ridtirud C, Hatanaka S, Chindaprasirt P. High calcium fly ash geopolymer mortar containing Portland cement for use as repair material. Constr Build Mater. 2015;98: 482-8.

[6] Singh B, Ishwarya G, Gupta M, Bhattacharyya SK. Geopolymer concrete: a review of some recent developments. Constr Build Mater. 2015;85:78-90.

[7] Sarker PK, Kelly S, Yao Z. Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete. Mater Des. 2014;63:584-92.

[8] Chindaprasirt P, Chalee W. Effect of sodium hydroxide concentration on chloride penetration and steel corrosion of fly ash-based geopolymer concrete under marine site. Constr Build Mater. 2014;63: 303-10.

[9] Pacheco-Torgal F, Abdollahnejad Z, Miraldo S, Baklouti S, Ding Y. An overview on the potential of geopolymers for concrete infrastructure rehabilitation. Constr Build Mater. 2012;36:1053-8.

[10] Zhang Z, Yao X, Zhu H. Potential application of geopolymers as protection coatings for marine concrete. Basic properties. Appl Clay Sci. 2010;49:1-6.

[11] Chindaprasirt P, Rattanasak U. Improvement of durability of cement pipe with high calcium fly ash geopolymer covering. Constr Build Mater. 2016;112:956-61.

[12] American Society for Testing and Materials. ASTM C33/C33M − 11 standard specification for concrete aggregates. USA: ASTM; 2011.

[13] American Concrete Institute. ACI 549.1R-93 guide for the design, construction, and repair of ferrocement. USA: ACI; 1993.

[14] American Concrete Institute. ACI 211.1-91 standard practice for selecting proportions for normal, heavyweight, and mass concrete. USA: ACI; 1991.

[15] Phoo-ngernkham T. Properties of high calcium fly ash geopolymer and its application as repair material [dissertation]. Khon Kaen, Thailand: Khon Kaen University; 2014.

[16] American Society for Testing and Materials. ASTM C192/C192M − 15 standard practice for making and curing concrete test specimens in the laboratory. USA: ASTM; 2015.

[17] Kaushik SK, Gupta VK, Rahman MK. Efficiency of mesh overlaps of ferrocement elements. J Ferrocem. 1987;17:329-36.

[18] Mander JB, Priestley MJ, Park R. Theoretical stress-strain model for confined concrete. J Struct Eng. 1988;114:1804-26.

[19] Xiao Y, Wu H. Compressive behavior of concrete confined by carbon fiber composite jackets. J Mater Civ Eng. 2000;12:139-46.

[20] Richart FE, Brandtzaeg A, Brown RL. The failure of plain and spirally reinforced concrete in compression. Technical report. Champaign, Illinois:Uni. of Illinois at Urbana Champaign, College of Engineering. Engineering Experiment Station; 1929. Report No. 190.

[21] Lam L, Teng JG. Design-oriented stress–strain model for FRP-confined concrete. Constr Build Mater. 2003;17:471-89.