Civil Engineering and Architecture 10(7): 2943-2952, 2022 http://www.hrpub.org
DOI: 10.13189/cea.2022.100713

Unit Weight, Strengths and Thermal Conductivity of Cellular Lightweight Fly Ash Geopolymer Mortar Reinforced with Polyvinyl Alcohol

Sermsak Tiyasangthong[1], Piyathida Yoosuk[1], Kitsada Krosoongnern[1], Bundit Krittacom[2], Prin Nachaisit[3], Cherdsak Suksiripattanapong[1,*]

[1]Infrastructure and Rail Transportation Technologies Research Unit, Department of Civil Engineering, Faculty of Engineering and Technology, Rajamangala University of Technology Isan, Nakhon Ratchasima, Thailand
[2]Development in Technology of Porous Materials Research Laboratory (DiTo-Lab), Department of Mechanical Engineering, Faculty of Engineering and Technology, Rajamangala University of Technology Isan, Nakhon Ratchasima, Thailand
[3]Faculty of Engineering, Rajamangala University of Technology Isan, Khon Kaen, Thailand

Received July 18, 2022; Revised August 12, 2022; Accepted October 11, 2022

Cite This Paper in the Following Citation Styles

(a): *[1] Sermsak Tiyasangthong, Piyathida Yoosuk, Kitsada Krosoongnern, Bundit Krittacom, Prin Nachaisit, Cherdsak Suksiripattanapong , "Unit Weight, Strengths and Thermal Conductivity of Cellular Lightweight Fly Ash Geopolymer Mortar Reinforced with Polyvinyl Alcohol," Civil Engineering and Architecture, Vol. 10, No. 7, pp. 2943 - 2952, 2022. DOI: 10.13189/cea.2022.100713.*

(b): *Sermsak Tiyasangthong, Piyathida Yoosuk, Kitsada Krosoongnern, Bundit Krittacom, Prin Nachaisit, Cherdsak Suksiripattanapong (2022). Unit Weight, Strengths and Thermal Conductivity of Cellular Lightweight Fly Ash Geopolymer Mortar Reinforced with Polyvinyl Alcohol. Civil Engineering and Architecture, 10(7), 2943 - 2952. DOI: 10.13189/cea.2022.100713.*

Abstract Lightweight materials are the most popular building wall construction materials because of their fast installation, high insulation, and low cost. However, these materials use cement as a binder. Cement production releases carbon dioxide emissions resulting in environmental issues. The research investigated the use of fly ash geopolymer and polyvinyl alcohol (PVA) to enhance the mechanical and thermal properties of cellular lightweight mortar. The effects of PVA concentrations, foam content (Fc), and curing time on properties of the cellular lightweight fly ash geopolymer (CLFAG) mortar reinforced with PVA specimens were evaluated. The results revealed that the PVA concentrations and Fc had an effect on the unit weights of the CLFAG reinforced with PVA specimens. The lowest unit weight of the specimens was 10.10 kN/m^3 at a PVA concentration of 20% and Fc of 2%. According to the Thailand industrial standard for C12 and C14 CLC block types, all mixed ingredients met the unit weight and compressive strength requirements. The correlation between unit weight and thermal conductivity of CLFAG reinforced with PVA specimens was represented by a linear function, which was a useful equation for estimating the thermal conductivity of specimens.

Keywords Cellular Lightweight Concrete, Fly Ash Geopolymer, Polyvinyl Alcohol, Thermal Conductivity

1. Introduction

The use of lightweight materials with low thermal conductivities in the building is continuously increasing because they can reduce the dead load of building structure [1,2] and energy consumption [3]. Many researchers have carried out properties of building walls, including cellular lightweight concrete [4], expanded polystyrene foam aggregate (EPS) concrete [5], phase change materials [6-9], and masonry units [10-14]. The cellular lightweight concrete, one of the lightweight materials, has lower unit weight and thermal conductivity than conventional materials (red brick, cement brick, and masonry unit) [15]. Borbon-Almada et al. [15]

investigated the thermal properties of a sample composed of cement, sand, and foam. They concluded that the addition of foam reduced the unit weight and thermal conductivity of the samples due to the large size of the pores [16]. To reduce CO_2 emissions and environmental issues from cement production, geopolymer can be utilized as a substitute for cement. Furthermore, the addition of polymers in lightweight materials can be used to improve their strength.

Lightweight geopolymer materials have been applied extensively, such as lightweight geopolymer concrete [17], lightweight geopolymer mortar [18-21], and lightweight geopolymer soil [22]. The optimum heat conditions of 65^{o}C for 72 hours were proposed by Suksiripattanapong et al. [22]. However, heat temperature resulted in consumption. To solve this problem, high calcium fly ash (FA) was used to improve the strength of geopolymer mortar due to its low energy consumption [3,18]. Yoosuk et al. [3] concluded that the cellular lightweight FA geopolymer mortar sample with 8 M NaOH gave maximum 7-day compressive strength and unit weight of 20.94 MPa and 14.34 kN/m^3, respectively. In addition, Wongkvanklom et al. [18] concluded that the unit weight, compressive strength of 28 days, thermal conductivity, and sound absorption coefficients were 844-2100 kg/m^3, 2.7-57.8 MPa, 0.13-1.62 W/mK, and 0.05-0.5, respectively. Suksiripattanapong et al. [2] introduced the utilization of bottom ash in cellular lightweight geopolymer mortar, demonstrating the lowest unit weight, highest compressive strength and lowest thermal conductivity of 11.08 kN/m^3, 16.98 MPa, and 0.15 W/mK, respectively. Recently, Adji [20] produced lightweight geopolymer concrete with concentrations of NaOH of 14 M and reported a unit weight of 14.53 kN/m^3, a strength of 19.2 MPa, and thermal conductivity of 0.27 W/mK.

Polyvinyl alcohol (PVA) has been widely used in construction materials [24-27] and ground improvement [28,29] to improve the flexural strength. However, the excessive PVA content (PVA/cement > 1) could lead to lower workability [27]. To manage this problem, the slump was controlled by varying superplasticizer content. Lee et al. [25] concluded that red clay mixed PVA's compressive strength and flexural strength were 16.57 and 3.02 MPa, respectively. The high strengths are because of hydrogen bonds. In addition, Al-Baghdadi et al. [24] evaluated the sulfate resistance of RCA concrete modified with PVA. They discovered that mixes with RCA and PVA had higher compressive strengths than control because more hydration products resulting from its water and PVA solution retention capacity, leading to improvement in microstructure [26].

Although much research has been conducted on cellular lightweight fly ash geopolymer and PVA in construction materials, the properties of cellular lightweight fly ash geopolymer (CLFAG) mortar reinforced with polyvinyl alcohol (PVA) have not been investigated. This research studied the using fly ash geopolymer and polyvinyl alcohol (PVA) to enhance the properties of cellular lightweight mortar. The influence parameters, including PVA concentration, foam content (Fc), and curing time, were investigated via unit weight, compressive and flexural strengths, and thermal conductivity.

2. Materials and Methods

2.1. Materials

Sand (S) was collected in Nakhon Ratchasima, Thailand. According to ASTM C778 [30], its specific gravity of 2.65 was measured. S had a fineness modulus of 2.33.

Fly ash (FA) with a specific gravity of 2.32 is a by-product of the electricity generation plant in Mae Moh, Thailand. The chemical components of FA are shown in Table 1 per ASTM E1621 [31]. The FA comprised 39.6% SiO_2, 12.69% Al_2O_3, 11.3% Fe_2O_3, and 29.44% CaO. The FA can be categorized as FA class C according to ASTM C618 [32].

The polyvinyl alcohol (PVA) was a white powder. PVA had a specific gravity of 1.27-1.31 and a molecular weight and 13,000 g/M [13]. The PVA concentration of 5, 10, 15, and 20% by water weight was used.

The liquid alkaline (L), sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were used. The NaOH concentration of 8 molars was kept.

Air foam agent (Sika Poro 40) was supplied by Sika (Thailand) Company Limited. Air foam was composed of foaming agent and water at a weight ratio of 1:40.

Table 1. Chemical compositions of FA

Chemical compositions	FA (%)
SiO_2	39.6
Al_2O_3	12.69
Fe_2O_3	11.3
CaO	29.44
MgO	N.D.
SO_3	3.01
Na_2O	0.96
K_2O	2.13
LOI	0.87

2.2. Specimen Preparation

The effect of variables, including PVA concentrations of 5, 10, 15, and 20%, foam content (Fc) of 0, 1, and 2%, and curing time of 7 and 28 days, on the properties of cellular lightweight fly ash geopolymer (CLFAG) mortar reinforced with PVA was evaluated. The L/FA ratio, Na_2SiO_3/NaOH, and NaOH concentration were fixed at

0.60, 2, and 8 molars, respectively. First, specimens of CLFAG reinforced with PVA were made by combining dry S and FA with L and PVA for 5 minutes. The sample was then blended for 5 minutes to achieve homogeneity after the addition of Fc. The CLFAG reinforced with PVA specimens were transferred into the mold with 50x50x50 mm and 40x40x160 mm, respectively. The specimens were covered in a vinyl sheet and cured at room temperature (27-30^{o}C) for 7 and 28 days. In accordance with ASTM C138 [33], ASTM C109 [34], ASTM C 348 [35], and ASTM E1225-04 [36], the unit weight, compressive strength, flexural strength, and thermal conductivity of CLFAG reinforced with PVA were evaluated.

3. Test Results

3.1. Unit Weight

Figure 1 indicates the 7-day and 28-day unit weights of the CLFAG reinforced with PVA specimens with different PVA concentrations and Fc. The test result showed that the 7-day and 28-day unit weight of the CLFAG reinforced with PVA specimens decreased with the increase in PVA concentrations. For instance, 7-day unit weight of the specimens at Fc of 2% is 10.96, 10.78, 10.59, 10.57, and 10.10 kN/m^3 for PVA concentrations of 0, 5, 10, 15, and 20%, respectively. This is due to the fact that PVA has lower specific gravity than both S and FA.

In addition, the increase in Fc resulted in the reduction of unit weight. This is due to the increase in the large size of pores, resulting in high porosity in sample increases [15]. For instance, the 7-day unit weight of specimens with PVA concentrations of 20% was 11.85, 11.10, and 10.10 kN/m^3 for Fc of 0, 1, and 2%, respectively. The 28-day unit weight of specimens was greater than the 7-day unit weight because the large size of pores was filled by geopolymerization products [1,2,22]. The lowest unit weight of the CLFAG reinforced with PVA specimens was found at PVA concentrations of 20% and Fc of 2%.

3.2. Compressive and Flexural Strengths

Figures 2 and 3 indicate the compressive and flexural strengths of the CLFAG reinforced with PVA specimens with different curing times, PVA concentrations and Fc. For all curing times, the strengths of the CLFAG reinforced with PVA specimens increased as PVA concentrations increased until PVA concentration was 5%. This is because they coexist with PVA films and geopolymerization products, resulting in strong bonding [23]. Beyond PVA concentration of 5%, specimens' compressive and flexural strengths decreased. For instance, the 7-day compressive strength of the specimens at Fc of 2% is 12.1, 12.8, 10.5, 9.6, and 6.8 MPa for PVA concentrations of 0, 5, 10, 15, and 20%, respectively. The excessive PVA concentration resulted in a large void in the specimens due to the high viscosity of PVA [26]. In addition, the excessive PVA concentration retarded the geopolymerization reaction [27].

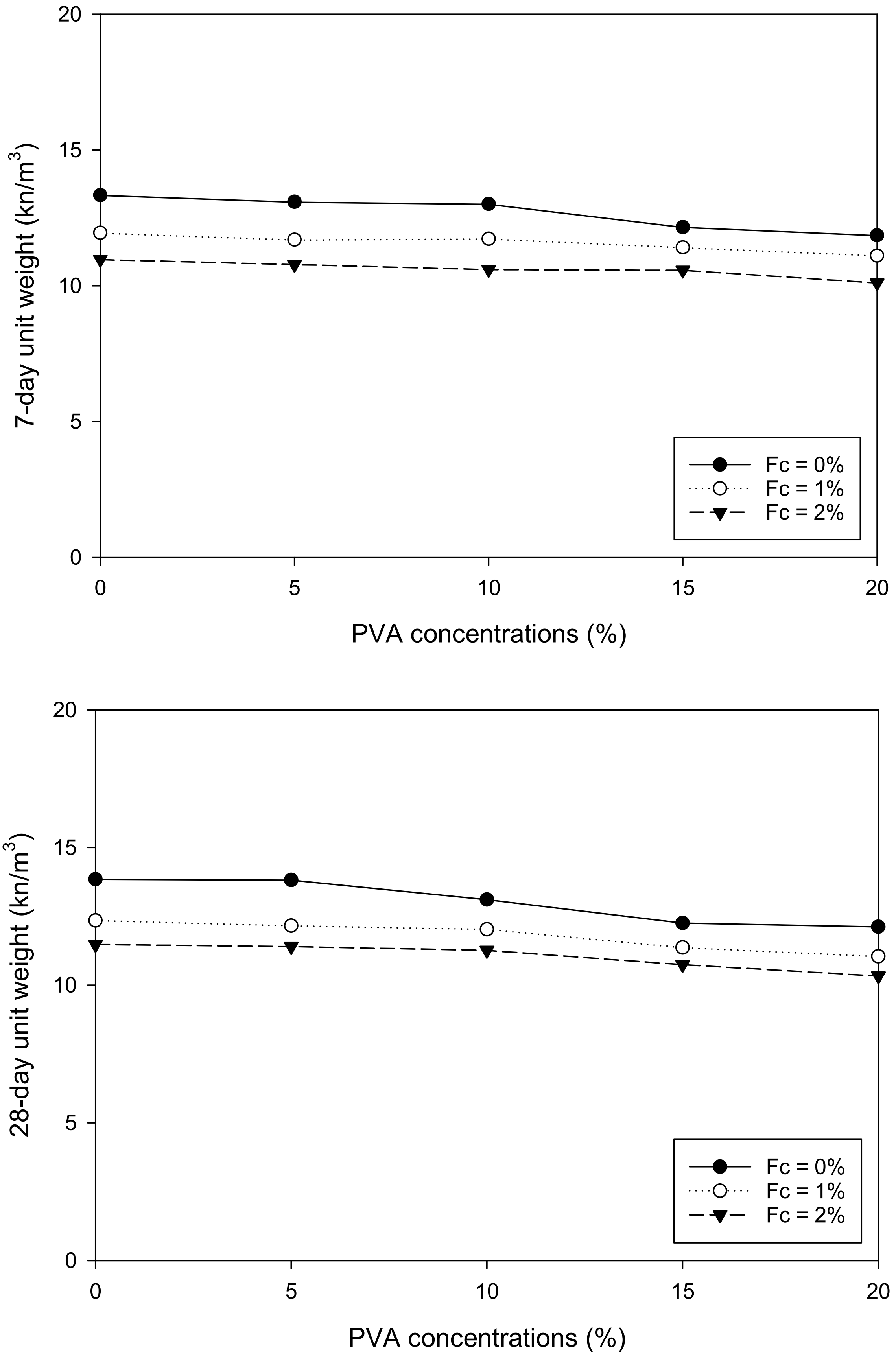


Figure 1. 7-day and 28-day unit weight of CLFAG reinforced with PVA specimens

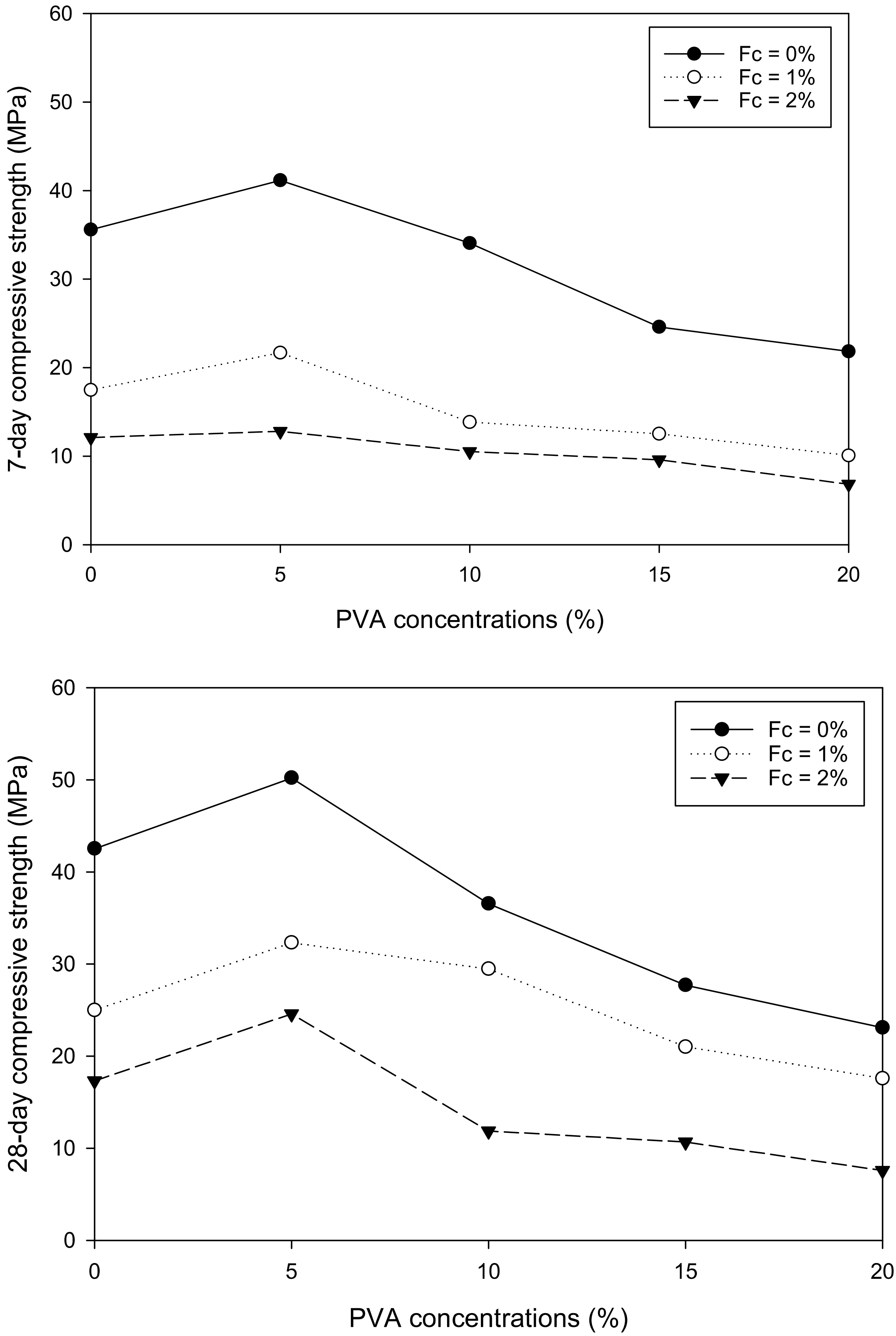


Figure 2. 7-day and 28-day compressive strength of CLFAG reinforced with PVA specimens

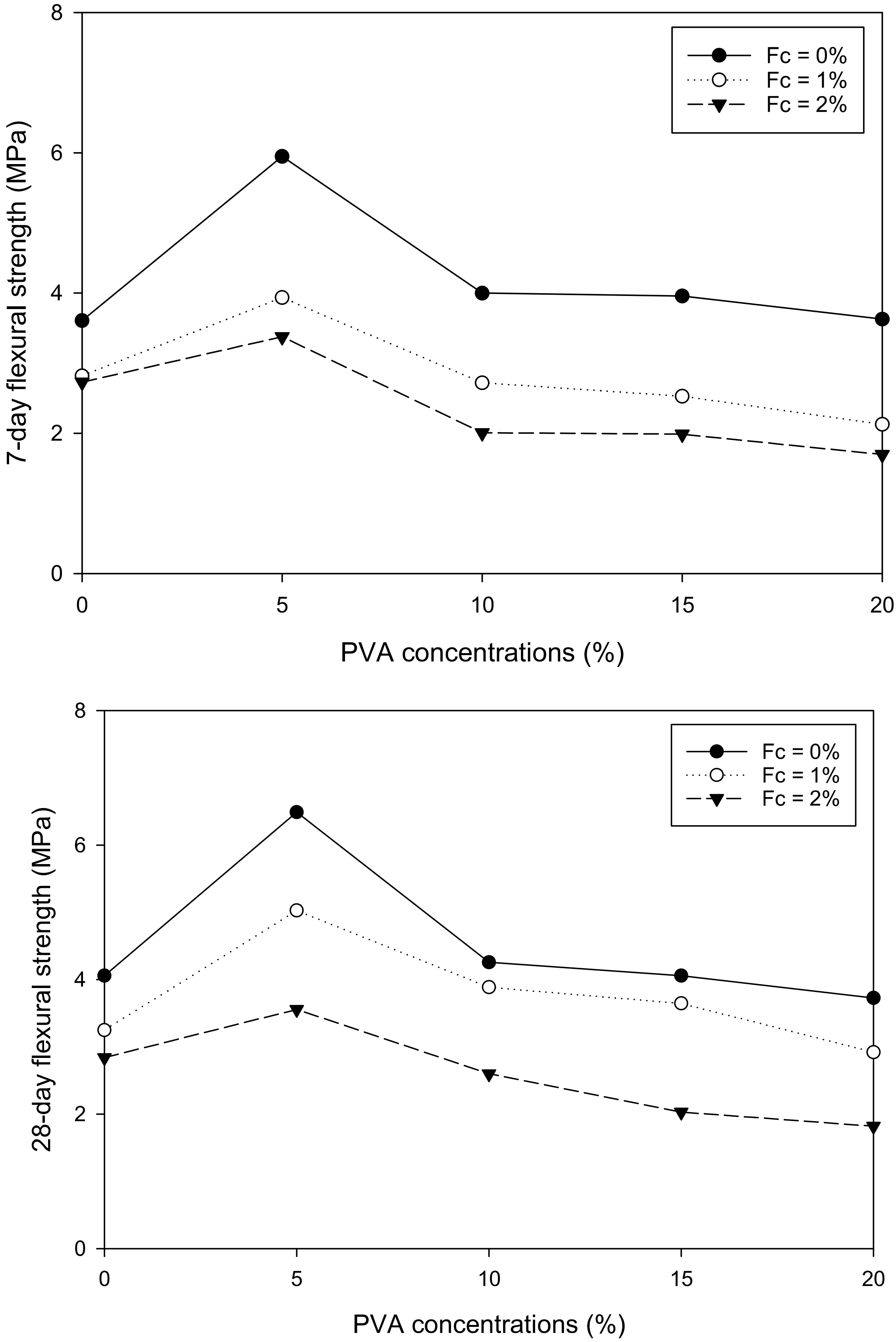


Figure 3. 7-day and 28-day flexural strength of CLFAG reinforced with PVA specimens

The effect of Fc on compressive and flexural strengths of the CLFAG reinforced with PVA specimens is indicated in Figures 2 and 3. Specimens' compressive and flexural strengths decreased as Fc increased for all PVA concentrations and curing times because of increased void in specimens [18]. The 28-day strengths of specimens were greater than the 7-day strengths because pozzolan and geopolymerization products are continuously increasing [1,2]. The maximum 28-day compressive and flexural strengths of specimens at PVA concentrations of 5% and Fc of 0% were 50 and 6.5 MPa, respectively. According to the Thailand industrial standard for cellular lightweight concrete blocks [2,22], all mix ingredients passed the unit weight (9.81-13.73 kN/m^3) and compressive strength requirement (2.5-5.0 MPa) for C12 and C14 CLC blocks types.

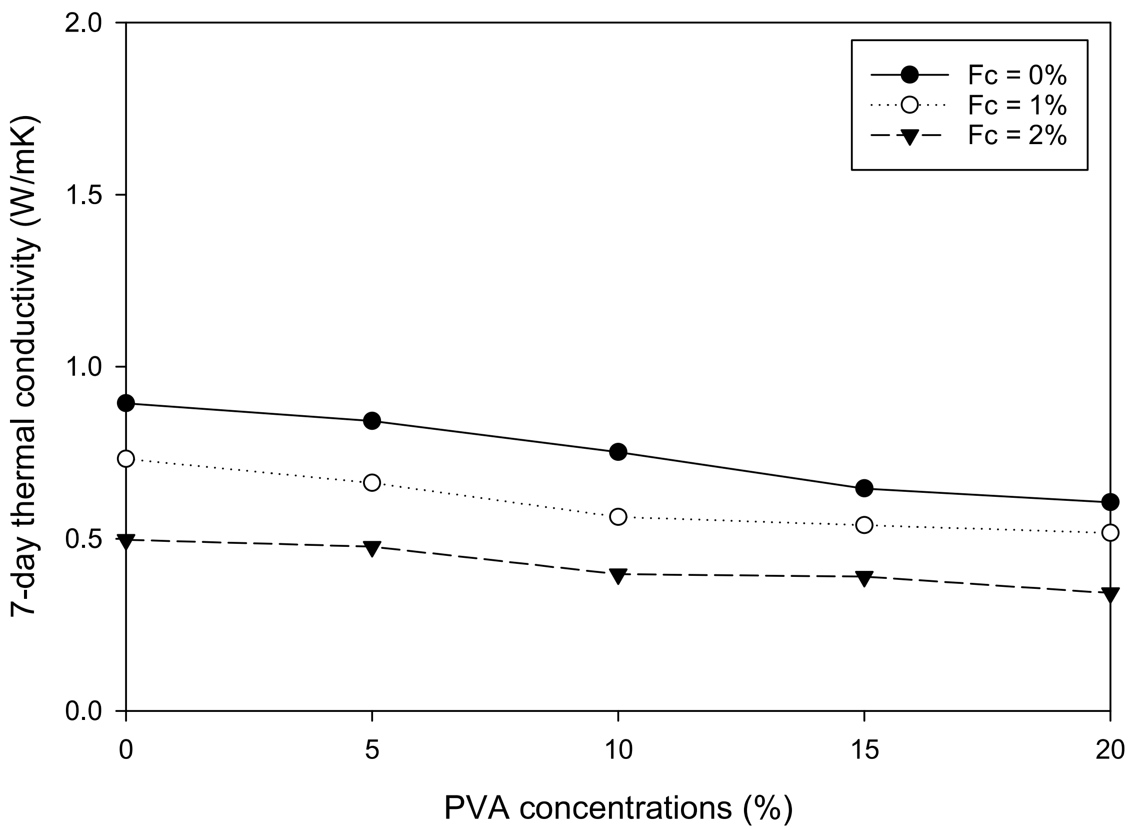
3.3. Thermal Conductivity

Figure 4 indicates the 7-day and 28-day thermal conductivity of the CLFAG reinforced with PVA specimens with different PVA concentrations and Fc. It is evident that the 7-day and 28-day thermal conductivity of the CLFAG reinforced with PVA specimens decreased as PVA concentration and Fc increased. For instance, 7-day thermal conductivity of the specimens at Fc of 2% is 0.497, 0.477, 0.397, 0.390, and 0.342 W/mK for PVA concentrations of 0, 5, 10, 15, and 20%, respectively. The higher concentration and Fc resulted in higher PVA films and large pores in specimens which prevent thermal transport [13].

Figure 5 indicates the correlation between thermal conductivity and unit weight of CLFAG reinforced with PVA specimens at different curing times, PVA concentrations, and Fc. It can be seen that the decrease in the unit weight of CLFAG reinforced with PVA specimens led to a reduction in heat conductivity. The correlation between unit weight and thermal conductivity of CLFAG reinforced with PVA specimens at various curing times, PVA concentrations, and Fc can be represented as a linear function in Eq. 1:

$$k = 0.0495\gamma \quad R^2 \text{ of } 0.941 \tag{1}$$

where k is the thermal conductivity (W/mK) and γ is the unit weight (kN/m^3).



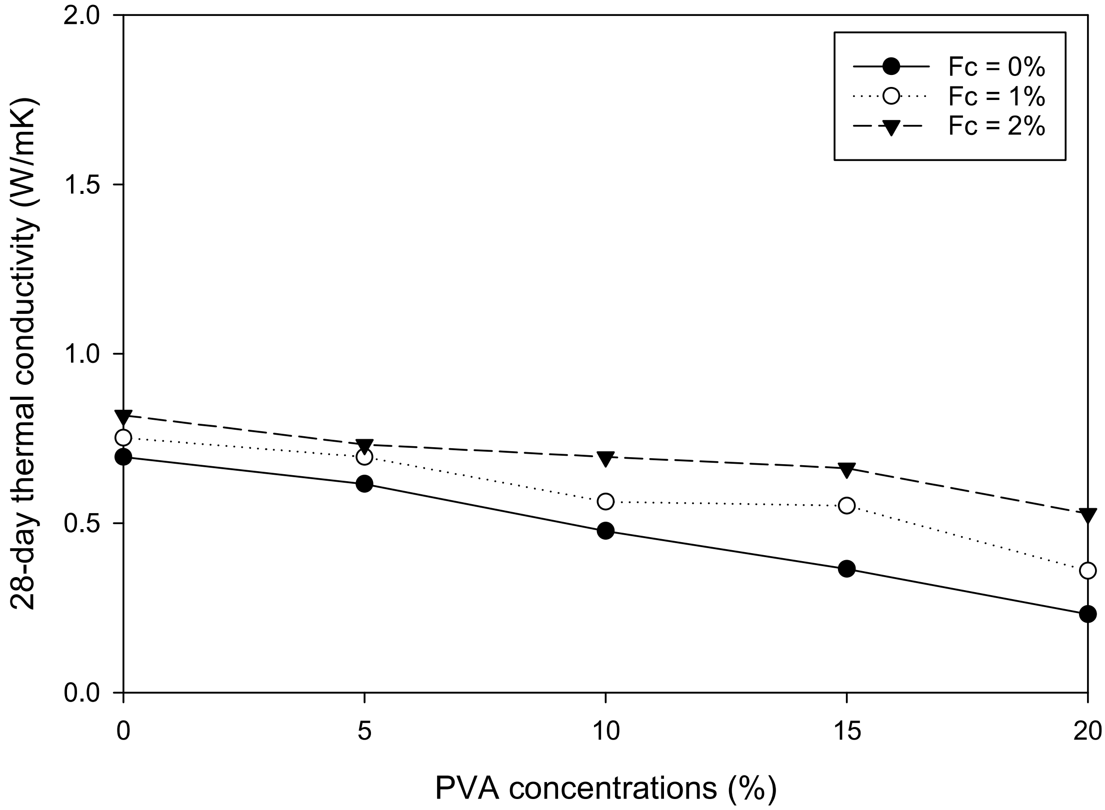


Figure 4. 7-day and 28-day thermal conductivity of CLFAG reinforced with PVA specimens.

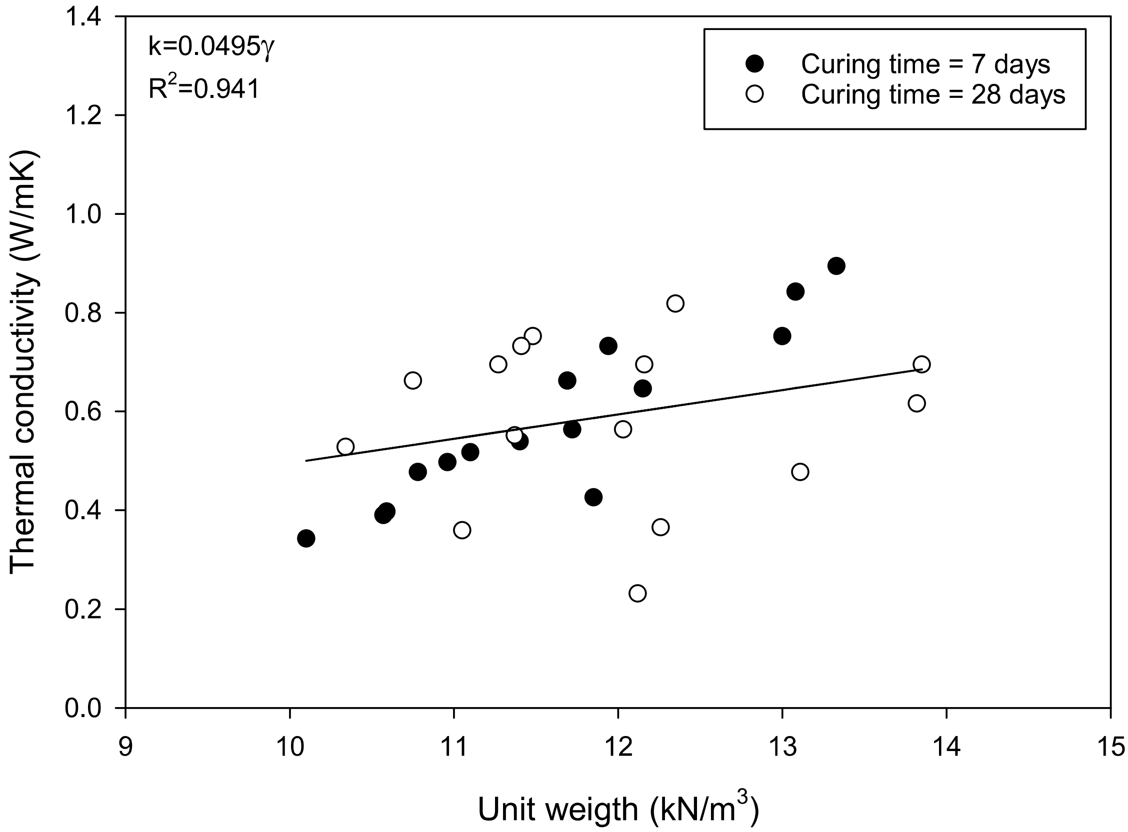


Figure 5. The correlation between thermal conductivity and unit weight

4. Conclusions

The properties of CLFAG specimens reinforced with PVA were analyzed. The conclusions are as follows:

1. The PVA concentrations and Fc had an effect on the unit weights of the CLFAG reinforced with PVA specimens. The specimens with a PVA concentration of 20% and Fc of 2% gave the lowest unit weight of 10.10 kN/m^3.
2. For all curing times, the compressive and flexural strengths of the CLFAG reinforced with PVA specimens increased as PVA concentrations increased until PVA concentration was 5%. Beyond PVA concentration of 5%, specimens' compressive and flexural strengths decreased.
3. All mix ingredients passed the unit weight (9.81-13.73 kN/m^3) and compressive strength (2.5-5.0 MPa) requirements according to the TIS for C12 and C14 CLC block types.
4. The 7-day and 28-day thermal conductivity of the CLFAG reinforced with PVA specimens decreased as PVA concentration and Fc increased because higher concentration and Fc resulted in higher PVA films and large pores in specimens which prevent the thermal transport.
5. The correlation between unit weight and thermal conductivity of CLFAG reinforced with PVA specimens at different curing times, PVA concentrations, and Fc could be expressed by a linear function which was a useful equation to estimate the thermal conductivity of CLFAG reinforced with PVA specimens.

Acknowledgments

This research project is supported by Thailand Science Research and Innovation (TSRI), contract No. FRB650059/NMA/21.

REFERENCES

[1] Yoosuk P., Suksiripattanapong C., Sukontasukkul P., Chindaprasirt P., "Properties of polypropylene fiber reinforced cellular lightweight high calcium fly ash geopolymer mortar," Case Studies in Construction Materials, vol. 15, 2021. DOI: 10.1016/j.cscm.2021.e0073 0

[2] Suksiripattanapong C., Krosoongnern K., Thumrongvut J. Sukontasukkul P., Horpibulsuk S., Chindaprasirt P., "Properties of cellular lightweight high calcium bottom ash-portland cement geopolymer mortar," Case Studies in Construction Materials, vol. 12, 2020. DOI: 10.1016/j.csc m.2020.e00337

[3] Khoukhi M., Hassan A., Abdelbaq S., "The impact of employing insulation with variant thermal conductivity on the thermal performance of buildings in the extremely hot climate," Case Studies in Thermal Engineering, vol. 16, 100562, 2019. DOI: 10.1016/j.csite.2019.100562

[4] Kadela M., Kukiełka A., Małek M., "Characteristics of Lightweight Concrete Based on a Synthetic Polymer Foaming Agent," Materials, vol. 13(21), 4979, 2020. DOI: 10.3390/ma13214979

[5] Obaid H.A., Hilal A.A., "Effect of Expanded Polystyrene Foam Aggregate on Strength and Shrinkage Characteristics of Foamed Concrete," Civil Engineering and Architecture, Vol. 10(5), pp. 1788-1797, 2022. DOI: 10.13189/cea.2022. 100507

[6] Liu Z., Hou J., Huang Y., Zhang J., Meng X., Dewancker B.J., "Influence of phase change material (PCM) parameters on the thermal performance of lightweight building walls with different thermal resistances," Case Studies in Thermal Engineering, vol. 31, 101844, 2022. DOI: 10.1016/j.csite.2022.101844

[7] Jia C., Geng X., Liu F., Gao Y., "Thermal behavior improvement of hollow sintered bricks integrated with both thermal insulation material (TIM) and Phase-Change Material (PCM)," Case Studies in Thermal Engineering, vol. 25, 100938, 2021. DOI: 10.1016/j.csite.2021.100938

[8] Sukontasukkul P., Nontiyutsirikul N., Songpiriyakij S., Sakai K., Chindaprasirt P., "Use of phase change material to improve thermal properties of lightweight geopolymer panel," Materials and Structures, vol. 49(11), pp. 4637-4645, 2016. DOI: 10.1617/s11527-016-0812-x

[9] Sukontasukkul P., Sutthiphasilp T., Chalodhorn W., Chindaprasirt P., "Improving thermal properties of exterior plastering mortars with phase change materials with different melting temperatures: paraffin and polyethylene glycol," Advances in Building Energy Research, vol. 13(2), pp. 220-240, 2018. DOI: 10.1080/17512549.2018.1488614

[10] Suksiripattanapong C., Horpibulsuk S., Phetchuay C., Suebsuk J., Phoo-ngernkham T., Arulrajah A., "Strength and durability of water treatment sludge–calcium carbide residue geopolymer as non-bearing masonry units," Journal of Materials in Civil Engineering, 2017. DOI: 10.1061/(ASCE)MT.1943-5533.0001944

[11] Hu W., Xia Y., Li F., Yu H., Hou C., Meng X., "Effect of the filling position and filling rate of the insulation material on the insulation performance of the hollow block," Case Studies in Thermal Engineering, vol. 26 2021. DOI: 10.1016/j.csite.2021.101023

[12] Tabyang W., Suksiripattanapong C., Wonglakorn N., Laksanakit C., Chusilp N., "Utilization of municipal solid waste incineration fly ash for non-bearing masonry units containing coconut fiber," Journal of Natural Fibers, 2022. DOI: 10.1080/15440478.2022.2073313

[13] Suksiripattanapong C., Jenpiyapong K., Tiyasangthong S., Krittacom B., Phetchuay C., Tabyang W., "Mechanical and thermal properties of lateritic soil mixed with cement and polymers as a non-bearing masonry unit," Case Studies in Construction Materials, vol. 16, 2022. DOI: 10.1016/j.cscm.2022.e00962

[14] Suksiripattanapong C., Srijumpa T., Horpibulsuk S., Sukmak P., Arulrajah A., Du Y.J., "Compressive strengths of water treatment sludge-fly ash geopolymer at various compression energies," Lowland Technology International,

vol. 17(3), pp. 147-156, 2015. DOI: 10.14247/lti.17.3_147

[15] Borbon-Almada A.D., Lucero-Alvarez J., Rodriguez-Muñoz N.A., Ramirez-Celaya M., Castro-Brockman S., Sau-Soto N., Najera-Trejo M., "Design and Application of Cellular Concrete on a Mexican Residential Building and Its Influence on Energy Savings in Hot Climates: Projections to 2050," Applied Sciences, vol. 10(8225), 2020. DOI: 10.3390/app10228225

[16] Yu W., Liang X., Ni F.M.W., Oyeyi A.G., Tighe S., "Characteristics of Lightweight Cellular Concrete and Effects on Mechanical Properties," Materials, vol. 13 (2678), 2020. DOI: 10.3390/ma13122678

[17] Saloma, Usman A.P., Hanafiah, Ramadhanty C.V., "The Durability of Lightweight Geopolymer Concrete (LGC) on Chloride Resistance," Civil Engineering and Architecture, vol. 10(5), pp. 1881-1890, 2022. DOI: 10.13189/cea.2022.100514

[18] Wongkvanklom A., Posi P., Kasemsiri P., Sata V., Cao T., Chindaprasirt P., "Strength, thermal conductivity and sound absorption of cellular lightweight high calcium fly ash geopolymer concrete," Engineering and Applied Science Research, vol. 48(4), pp. 487-496, 2021. DOI: 10.14456/easr.2021.51

[19] Tayeh B.A., Zeyad A.M., Agwa I.S., Amin M., "Effect of elevated temperatures on mechanical properties of lightweight geopolymer concrete," Case Studies in Construction Materials, vol. 15, 2021. DOI: 10.1016/j.cscm.2021.e00673

[20] Sutama A., Saggaff A., Saloma, Hanafiah, "Properties and Microstructural Characteristics of Lightweight Geopolymer Concrete with Fly Ash and Kaolin," International Journal of Scientific & Technology Research, vol. 8(07), 2019. URL: http://repository.unsri.ac.id/id/eprint/33445

[21] Maho B., Sukontasukkul P., Sua-Iam G., Sappakittipakorn M., Intarabut D., Suksiripattanapong C., Chindaprasirt P., Limkatanyu S., "Mechanical properties and electrical resistivity of multiwall carbon nanotubes incorporated into high calcium fly ash geopolymer," Case Studies in Construction Materials, vol. 15, 2021. DOI: 10.1016/j.cscm.2021.e00785

[22] Suksiripattanapong C., Horpibulsuk S., Boongrasan S., Udomchai A., Chinkulkijniwat A., Arulrajah A., "Unit weight, strength and microstructure of water treatment sludge-fly ash lightweight cellular geopolymer," Construction and Building Materials, vol. 94, pp. 807-816, 2015b. DOI: 10.1016/j.conbuildmat.2015.07.091

[23] Suksiripattanapong C., Horpibulsuk S., Yeanyong C., Arulrajah A., "Evaluation of polyvinyl alcohol and high calcium fly ash based geopolymer for the improvement of soft Bangkok clay," Transportation Geotechnics, vol. 27, 2021. DOI: 10.1016/j.trgeo.2020.100476

[24] Al-Baghdadi H.M., "Experimental study on sulfate resistance of concrete with recycled aggregate modified with polyvinyl alcohol (PVA)," Case Studies in Construction Materials, Vol. 14, (2021). DOI: 10.1016/j.cscm.2021.e00527

[25] Lee K.C., Her J.H., Kwon S.K., "Red clay composites reinforced with polymeric binders," Construction and Building Materials, Vol. 22, pp. 2292-2298, 2008. DOI: 10.1016/j.conbuildmat.2007.10.008

[26] Allahverdi A., Kianpur K., Moghbeli M.R., "Effect of polyvinyl alcohol on flexural strength and some important physical properties of Portland cement paste," Iranian Journal of Materials Science & Engineering, vol. 7(1), pp. 1–6, 2010. URL: http://ijmse.iust.ac.ir/article-1-223-en.html

[27] Yaowara T., Horpibulsuk S., Arulrajah A., Mirzababaei M., Rashid A.S.A., "Compressive and flexural strength of polyvinyl alcohol modified pavement concrete using recycled concrete aggregates," Journal of Materials in Civil Engineering, vol. 30(4), 2017. DOI: 10.1061/(ASCE)MT.1943-5533.0002233

[28] Horpibulsuk S., Wijitchot A., Neramitkornburee A., Shen S.L., Suksiripattanapong C., "Factors influencing unit weight and strength of lightweight cemented clay," Quarterly Journal of Engineering Geology and Hydrogeology, vol. 47(1), 2014. DOI: 10.1144/qjegh2012-069

[29] Mirzababaeia M., Arulrajah M., Horpibulsuk S., Soltani A., Khayat N., Stabilization of soft clay using short fibers and polyvinyl alcohol," Geotextiles and Geomembranes, vol. 46, pp. 646–655, 2018. DOI: 10.1016/j.geotexmem.2018.05.001

[30] ASTM C778. Standard specification for standard sand. URL: https://www.astm.org/c0778-21.html

[31] ASTM E1621. Standard Guide for Elemental Analysis by Wavelength Dispersive X-Ray Fluorescence Spectrometry. URL: https://www.astm.org/e1621-21.html

[32] ASTM C618-19. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. URL: https://www.astm.org/c0618-19.html

[33] ASTM C138/C138M. Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. URL: https://www.astm.org/astm-tpt-192.html

[34] ASTM C109/109M-21. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). URL: https://www.astm.org/c0109_c0109m-21.html

[35] ASTM C348-21. Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars. URL: https://www.astm.org/c0348-21.html

[36] ASTM E1225-20. Standard Test Method for Thermal Conductivity of Solids Using the Guarded-Comparative-Longitudinal Heat Flow Technique. URL: https://www.astm.org/e1225-20.html