บทความวิจัย

สมรรถนะของมอร์ตาร์มวลรวมน้ำหนักเบาใส่พูมิซผสมตะกรันเถ้าเชื้อเพลิงปาล์มน้ำมันและดินขาวแปรสำหรับทนต่ออุณหภูมิที่สูงขึ้นและการไหลผ่านของคลอไรด์

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บทคัดย่อ

งานวิจัยนี้เกี่ยวกับการศึกษาสมรรถนะของมอร์ตาร์มวลรวมน้ำหนักเบาใส่พูมิซผสมตะกรันเถ้าเชื้อเพลิงปาล์มน้ำมันและดินขาวแปรต่อการทนไฟและต้านการซึมผ่านของคลอไรด์ โดยใช้ตะกรันเถ้าเชื้อเพลิงปาล์มน้ำมันและดินขาวแปรแทนที่ปริมาณปูนซีเมนต์ปอร์ตแลนด์ธรรมดา ชนิดที่ 1 ในอัตราส่วนร้อยละ 0, 10, 20 และ 30 โดยมวล ที่อัตราส่วนน้ำต่อวัสดุประสาน 0.35 บ่มตัวอย่างมอร์ตาร์ที่บรรยากาศห้อง เป็นระยะ 3, 7, 28, 56 และ 90 วัน ทดสอบกำลังอัดและการสูญเสียน้ำที่อุณหภูมิห้องและอุณหภูมิที่สูงขึ้น (200 และ 400 องศาเซลเซียส) ด้วยมอร์ตาร์ทรงลูกบาศก์ขนาด 50 × 50 × 50 มิลลิเมตร หล่อมอร์ตาร์ทรงกระบอกขนาด 100 × 50 มิลลิเมตร สำหรับทดสอบการซึมผ่านได้ของคลอไรด์ พบว่า มอร์ตาร์ผสมดินขาวแปรร้อยละ 20 มีกำลังอัดสูงสุดที่อุณหภูมิห้องและที่อุณหภูมิ 400 องศาเซลเซียส มีค่าการนำความร้อนต่ำกว่าตัวอย่างควบคุม และมีการซึมผ่านได้ของประจุคลอไรด์ต่ำที่สุด สำหรับตัวอย่างผสมตะกรันเถ้าเชื้อเพลิงปาล์มน้ำมันและดินขาวแปรร้อยละ 10 มีสมรรถนะเชิงกลมากกว่าตัวอย่างควบคุม เมื่อวิเคราะห์ด้วยภาพถ่ายจุลทรรศน์อิเล็กตรอนแบบส่องกราด พบว่า C-S-H และ C-A-H ซึ่งได้จากปฏิกิริยาไฮเดรชันและปฏิกิริยาปอซโซลาน ช่วยพัฒนาสมรรถนะเชิงกล สามารถทนต่ออุณหภูมิสูง และลดการไหลผ่านของประจุคลอไรด์

คำสำคัญ: พูมิซ ตะกรันเถ้าเชื้อเพลิงปาล์มน้ำมัน ดินขาวแปร อุณหภูมิที่สูงขึ้น คลอไรด์

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Research Article

Performance of Lightweight Aggregate Mortar Containing Pumice Blended with Palm Oil Fuel Ash Clinker and Metakaolin for Elevated Temperatures and Chloride Permeability Resistance

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Abstract

This research aims to investigate the performance of lightweight aggregate mortar containing pumice blended with palm oil fuel ash clinker and metakaolin for elevated temperatures and chloride permeability resistance. Specimens were carried out by replacing Ordinary Portland cement with palm oil fuel ash clinker and metakaolin at a percentage of 0, 10, 20 and 30 by weight of binder. The water to binder ratio of 0.35 was fixed for all specimens. Specimens were cured in ambient temperature for the period of 3, 7, 28, 56 and 90 days. The compressive strength and water losing value in ambient and elevated temperatures (200 and 400 °C) were determined for hardened cubic specimens in size of 50 × 50 × 50 mm. Rapid chloride permeability test was determined with 100 × 50 mm cylindrical specimen. The specimen blended with 20% metakaolin content has the highest compressive strength in ambient temperature and at 400 °C; the thermal conductivity value is also lower than the control specimen. Moreover, the rapid chloride permeability test provided the lowest chloride ion charge passed. The specimen blended with 10% palm oil fuel ash clinker incorporating metakaolin has surpassed compressive strength than the control specimen. SEM microphotographs recognized C-S-H and C-A-H crystals which are products from hydration and pozzolanic activity that uphold the mechanical performance, resist elevated temperature and suppress the charge passed.

Keywords: Pumice, Palm Oil Fuel Ash Clinker, Metakaolin, Elevated Temperatures, Chloride

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1. Introduction

Strength and durability of the building structures are extremely important which affects life and property. In 25 years from 1989 to 2013, building collapse was caused by the fire at 10.9 percent [1]. In addition to the building fire problem, the corrosion of buildings from seawater was also a problem that affected the durability of building and infrastructures as well. Specifically, building located on the coastal area in Thailand which has 23 provinces or a coastline of 2,815 kilometers [2].

The durable building materials such as the concrete can withstand high heat from fire and chloride ion permeability from seawater at the same time. Therefore, a supplementary cementitious material is used to increase the resistance of high temperature and chloride ion permeability. Pozzolanic material is a material which has high silica, alumina and combination compound and extensively used as a supplementary cementitious materials. Thus, concrete or mortar blended with pozzolanic material has improved the strength and environmental corrosion resistance [3].

Palm oil is an industrial crop in Thailand, Malaysia, Indonesia, etc. Palm oil is used for producing biodiesel and being applied in the food industry [4]. Palm oil plantations and palm oil factories are built to meet the current needs. Waste from the palm oil extraction process is mesocarp palm fiber which is used as fuel for the boiler to produce steam and generate electricity for using in the factory. By product from this process, it is a palm oil fuel ash clinker. Palm oil fuel ash clinker is left and used for landfills that cause the environmental problems as well as disposal area. Palm oil fuel ash clinker is mainly composed of silicon dioxide.

Metakaolin is thermally treated kaolinite at 700–800 °C of dehydroxylation which has high silica and alumina content so it is also a pozzolanic material [5]. The silica and alumina from pozzolanic materials react with calcium hydroxide ($Ca(OH)_2$) to form C-S-H and C-A-H gel [6] that are derived from pozzolanic reaction. The production of pozzolanic activity enhances physical and mechanical properties such as low water permeability, high compressive strength, high durability, etc [7]-[9]. Hence, palm oil fuel ash clinker and metakaolin can be used as supplementary cementitious materials.

Pumice is suitable to use as aggregate for lightweight concrete or mortar. The porous structure of pumice improves the heat insulation property and reduces unit weight of the concrete or mortar. Their highly porous causes high adhesion between matrix and pumice aggregate which develop the strength at the interfacial transition zone. Moreover, Lightweight concrete or mortar can be easily transported, and they also aided to minimize the construction cost [10].

Consequently, using pumice as lightweight aggregate, palm oil fuel ash clinker and metakaolin as supplementary cementitious materials, they are not only be improving mechanical and physical performance but also solving environmental problems. In addition, the construction period is probably much faster due to construction material is lighter which resulted in reducing construction costs as well. This research is in regarded to compressive strength, water losing, elevated temperatures resistance and Rapid Chloride Permeability Test (RCPT) of mortar specimens.

2. Materials and Methods

2.1 Materials preparation

This research used Ordinary Portland Cement (OPC) according to TIS (type 1). Palm oil fuel ash clinker (P) was waste from the boiler of palm oil extraction factory at Pattani province. It has grayish-black in color with size about 10 cm [Figure 1(a), (b)] and the specific gravity of lump is 1.23. Kaolinite is supplied from The Mineral Resources Development Co., Ltd. at Ranong province, Thailand. Pumice aggregate has specific gravity of 1.43 which was purchased from a commercial agent. Palm oil fuel ash clinker were crushed and grounded by rotary crusher and jar mill for sieved to pass 45 µm sieve. Metakaolin (M) was thermally treated with an electric furnace at 800 °C for 1 hour. Whitish-yellow kaolinite becomes to whitish-orange color after calcination [Figure 1 (c)–(d)]. Pumice aggregate was sieved and used as fine aggregate with the maximum size of 4.75 mm according to ASTM C33 [11].

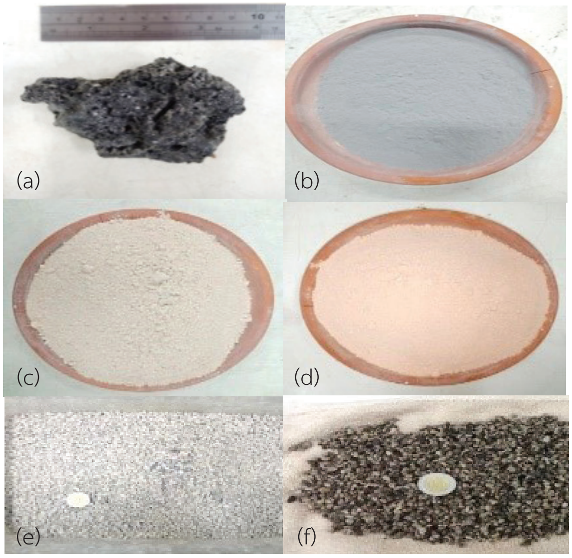

Figure 1 Palm oil fuel ash clinker in raw lump (a) and grind powder (b), color of Kaolinte (c) and metakaolin (d), pumice aggregate in dry (e) and pre-wet (f).

2.2 Specimens preparation

Specimens were carried out by partial replacing OPC with P and M and both PM at a percentage of 0, 10, 20 and 30 by weight of binder. Pumice aggregate was prepared by washing until clean and soaking in water for 6 hours then mopped it with cloth for 1 hour (prewetting) in order to prevent water absorption during hydration of OPC which is depicted in Figure 1(e), (f). The water absorption capacity of pumice aggregate was about 40%. This research used pumice as fine aggregate of 400 kg/m^3. The water to binder ratio (w/b) was regarded of 0.35 was considered for all specimens (totally, w/b is about 0.75). The binder to aggregate ratio is 0.5. Mortar mixing designs of all specimens are shown in Table 1 which is applied from ACI 211 standard [12]. Cubic mortar specimen was cast using 50 × 50 × 50 mm for compressive strength and water losing test. Cylindrical specimen of 100 diameter by 50 mm height was used for rapid chloride permeability test. Wrapped – plastic specimens cured in ambient temperature (25–28°C) with a relative humidity of 75–80% and were tested at the age of 3, 7, 28, 56 and 90 days.

2.3 Test procedures

The chemical compositions of the material was analyzed by X-ray fluorescence spectrometer (XRF) (Zetium Panalytical) which is shown in Table 2 Both palm oil fuel ash clinker and metakaolin can be classified as pozzolanic material class C and class F, respectively. [13].

Table 1 Mortar mixing designs in this study

Code	Content (kg/m³)				
	OPC	P	M	PA	Water
OPC	800	-	-	400	280
P10	720	80	-	400	280
P20	640	160	-	400	280
P30	560	240	-	400	280
M10	720	-	80	400	280
M20	640	-	160	400	280
M30	560	-	240	400	280
PM10	720	40	40	400	280
PM20	640	80	80	400	280
PM30	560	120	120	400	280

Note: OPC = Ordinary Portland Cement (Type 1), P = Palm Oil Fuel Ash Clinker, M = Metakaolin and PA = Pumice Aggregate

Table 2 Chemical compositions and true density of OPC, palm oil fuel ash clinker and metakaolin

Oxide Composition	Chemical Composition (%)		
	OPC	P	M
Silicon dioxide (SiO_2)	15.76	53.56	52.47
Aluminum oxide (Al_2O_3)	3.28	0.91	42.37
Iron(III) oxide (Fe_2O_3)	3.83	1.85	1.57
Calcium oxide (CaO)	64.96	15.21	0.03
Magnesium oxide (MgO)	1.05	7.09	0.15
Phosphorus pentoxide (P_2O_5)	0.09	5.08	0.06
Potassium oxide (K_2O)	0.47	9.85	2.33
Sulfur trioxide (SO_3)	3.38	0.52	0.03
True density (kg/m³)	3,052	2,549	2,573

The true density was measured by multi-pycnometer machine that is shown in Table 2. True density is density of particle which is not including open and close pores. The true density of palm oil fuel ash clinker and metakaolin are lower than OPC. Thus, effect of OPC instead with palm oil fuel ash clinker and metakaolin reduced the weight of mortar specimens.

The particle size was analyzed by Laser Particle

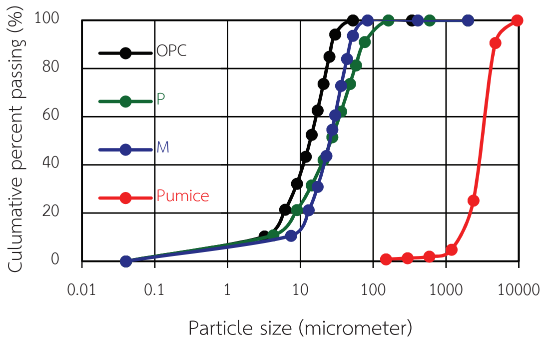

Figure 2 Particle size distribution of materials.

Size Analyzer (LPSA), LS 230, COULTER. OPC, palm oil fuel ash and metakaolin have average particle size of 14.61, 33.47 and 26.77 μm, respectively, which are shown in Figure 2. Pumice has average particle size of 3.28 mm.

The assessment of mortar specimens including compressive strength and water losing at ambient and elevated temperatures including chloride permeability resistance that were determined.

The microstructure of the specimens at curing ages 28 days was also analyzed by scanning electron microscope (SEM model XMAX-Quanta400).

Water losing of the specimens was estimated by percentage of different weight before and after curing periods, can be compute in Equation (1).

$$W = ((W_b - W_a) / W_a) \times 100 \quad (1)$$

Where W is water losing's percentage. W_b and W_a are weight of the specimens before and after curing.

The compressive strength of the specimens was measured by a compression testing machine (capacity 1500 kN) according to ASTM C109 [14]. The specimens were heated at 200 °C and 400 °C for 2 hours

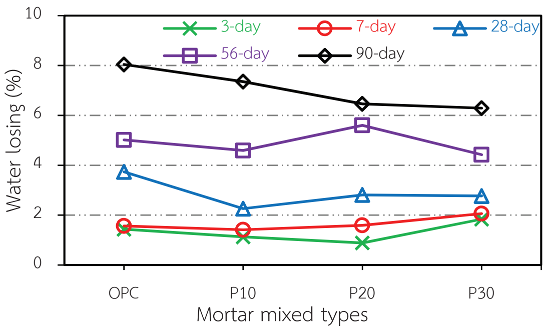

Figure 3 Water losing of mortar specimens blended with palm oil fuel ash clinker at different ages.

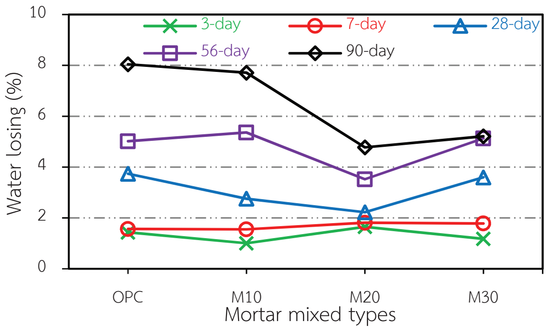

Figure 4 Water losing of mortar specimens blended with metakaolin at different ages.

to determine elevated temperatures resistance performance using an electric furnace. Chloride permeability resistance of mortar investigated Rapid Chloride Permeability Test (RCPT) according to ASTM C-1202 [15].

3. Results and Discussion

3.1 Water losing at ambient temperature

Figure 3–5 shows the increment of the curing period resulted in the water losing of mortar specimens increased due to water evaporation.

Water losing value of P10 specimen is 2.26% which was lower than the other specimens blended with palm oil fuel ash clinker at curing age 28 days. Increasing contents of palm oil fuel ash clinker in the specimens increased water losing value. However, the water losing value of specimen blended with palm oil fuel ash clinker was lower than the control specimen in long term periods. It could be noted that palm oil fuel ash clinker could reduce the water losing of mortar specimens.

An increase contents of metakaolin resulted to increase water losing value at initial curing periods. Water losing decreased when the metakaolin content increased in long term curing period. Especially, the 20%M specimen has the lowest water losing value which is 2.23, 3.52 and 4.78% at 28, 56 and 90 days, respectively (Figure 4). The specimen containing metakaolin more than 20% effected on increasing water losing but it is still lower than the control specimen.

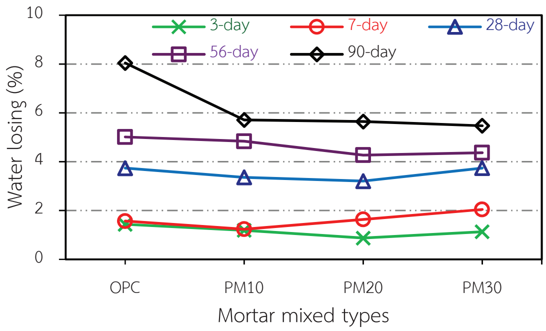

Figure 5 Water losing of mortar specimens blended with palm oil fuel ash clinker and metakaolin at different ages.

The water losing value of palm oil fuel ash clinker incorporated with metakaolin specimens similar to metakaolin specimens (Figure 5). The PM20 specimen shows low water losing value results at 28 and 56 days. Nevertheless, the increment of palm oil fuel ash clinker incorporated with metakaolin decreased water losing at curing age of 90 days.

The pozzolanic and hydration's product conduct like filler agent in the pore of specimens. That is the most probable interpretation of this situation reduced the size of pore in mortar specimens and affected on low water losing [16], [17].

It could be noted that palm oil fuel ash clinker and metakaolin could reduce water losing of mortar specimens. The decreasing of water losing resulted in mortar specimens to have sufficient water for hydration and pozzolanic activity. Primary activity is hydration activity from OPC reaction with water that caused the primary C-S-H and $Ca(OH)_2$. The secondary step is pozzolanic activity from which silica or alumina in pozzolanic materials reaction with $Ca(OH)_2$ to form secondary C-S-H or C-A-H that improved physical and mechanical properties of the specimens [6], [18]. The pozzolanic activity can be expressed as following below in (2), (3) [6].

$$3[Ca(OH)_2] + 2[SiO_2] = [3(CaO)\bullet 2(SiO_2)\bullet 3(H_2O)] \quad (2)$$

$$3[Ca(OH)_2] + Al_2O_3 + 3[H_2O] = [3(CaO)\bullet Al_2O_3\bullet 6(H_2O)] \quad (3)$$

3.2 Compressive strength at ambient temperature

An increase of curing periods causes compressive strength increased as depicted in Figure 6. The result shows a reduction of compressive strength at initial curing periods when palm oil fuel ash clinker contents increased.

Nonetheless, the P10 specimen has the highest compressive strength of 17.10 and 17.33 MPa at the curing age of 28 and 56 days, respectively. Due to the product of pozzolanic and hydration activity, the compressive strength of specimens was improved [9]. This is caused from porosity reduction in Figure 3 [16]. Furthermore, the curing ages of 90 days, both of P20 and P30 specimens display increasing of compressive strength of 18.24 and 18.89 MPa, respectively. Due to the high content of palm oil fuel ash clinker which is pozzolanic material, that carries on a long period for pozzolanic activity to approach the highest compressive strength [19].

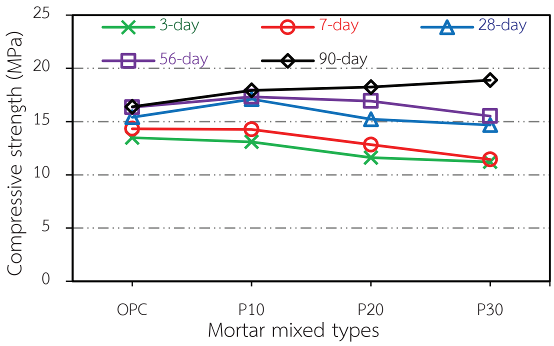

Figure 6 Compressive strength of mortar specimens blended with palm oil fuel clinker at different ages.

The result in Figure 7 shows the increasing content of metakaolin influenced the increase of compressive strength. Especially, M20 specimen has the highest compressive strength value of 15.90, 20.79, 21.69 and 23.25 MPa at curing age of 7, 28, 56 and 90 days, respectively. The compressive strength increased due to the filler effect from the product of hydration and pozzolanic activity (primary C-S-H, secondary C-S-H and C-A-H) [8], [18]. Nevertheless, the specimen contained metakaolin more than 20% provided decreasing compressive strength. The porosity of specimens increased from

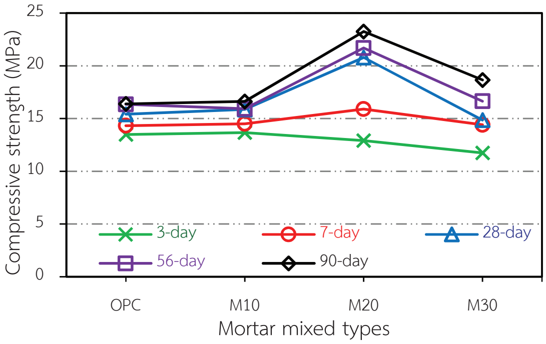

Figure 7 Compressive strength of mortar specimens blended with metakaolin at different ages.

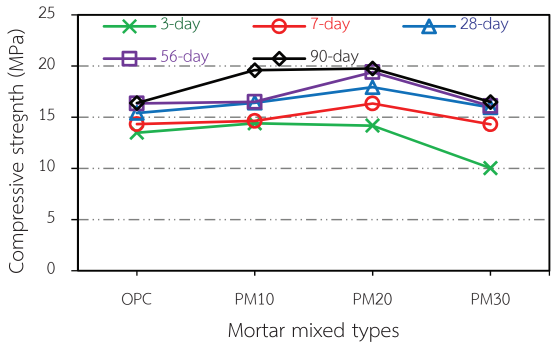

Figure 8 Compressive strength of mortar specimens blended with palm oil fuel ash clinker and metakaolin at different ages.

excessive metakaolin content [8]. The optimum metakaolin content for OPC partial replacement was also reported by Nadeem *et al.* [20]. Besides, the result according with water losing value as shown in Figure 4 exhibited the lowest water losing value belonging M20 specimen.

The result of the compressive strength of the specimen blended with palm oil fuel ash clinker incorporated with metakaolin as shown in Figure 8 was familiar to the compressive strength of metakaolin specimens (Figure 7). The PM20 provided the highest compressive strength value of 16.34, 17.94, 19.41 and 19.76 MPa regarding at age of 7, 28, 56 and 90 days, respectively. It is according with water losing value decreased in Figure 5.

3.3 Water losing at elevated temperatures

After determination of specimens at ambient temperature the dominant specimens were carried out elevated temperatures and chloride permeability resistance. The OPC, P10, M20 and PM20 specimens at curing age of 28 days were selected in reason of their highest compressive strength value.

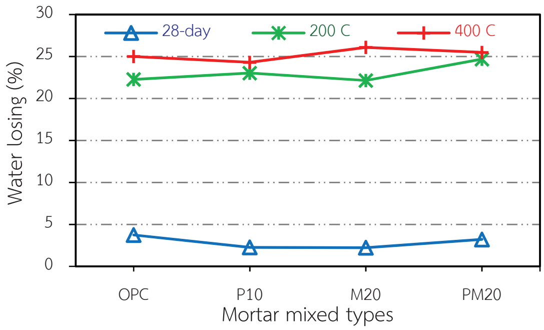

Figure 9 Water losing of mortar specimens at elevated temperatures.

The water losing of specimens at elevated temperatures are revealed in Figure 9. Increment of water losing value derived from elevated temperature owing to evaporation of capillary water and chemically combined water inner specimens [20]. The elevated temperatures influenced on C-S-H dehydration and $Ca(OH)_2$ decomposition [21], [22]. The $Ca(OH)_2$ remnant can be expressed in chemical Equation (4) [22].

$$Ca(OH)_2 \rightarrow CaO + H_2O \qquad (4)$$

At 200 °C, OPC specimen has water losing value of 22.27% and the mortar specimen that has water losing value lower than the OPC specimen belong to M20. Besides, the M20 specimen has also the lowest water losing value which is 22.14%. At 400 °C, M20 specimen has become the highest water losing value which is 26.09% owing to raise open internal pore of the specimens which was also noticed by Nadeem *et al.* [20].

Comparisons between P10 and OPC specimen have water losing value of 24.31% and 25.01%, respectively. When $Ca(OH)_2$ decomposed to CaO resulted in crack expansion inside the specimens owing to the volume increased [22]. Thus, the decrement of $Ca(OH)_2$ from pozzolanic activity following in (2)–(3) decreased the crack at elevated temperatures. The water losing decreased due to the reduction of porosity [23].

The elevated temperatures are also caused the shrinkage of specimens. The OPC specimen has shrinkage value of 2.26% while the P10 has a shrinkage value of 2.11% which low different. The evaporation of water including the bond between pumice and cement paste at Interfacial Transition Zone (ITZ) reasoned shrinkage of specimens [24].

3.4 Compressive strength at elevated temperatures

Figure 10 presents the reduction of compressive strength value of mortar specimens in high temperature. The micro-crack of mortar specimens increased owing to evaporation of water which consist of $Ca(OH)_2$. The micro-crack could become large and deterioration of C-S-H that caused compressive strength decreasing [19], [20].

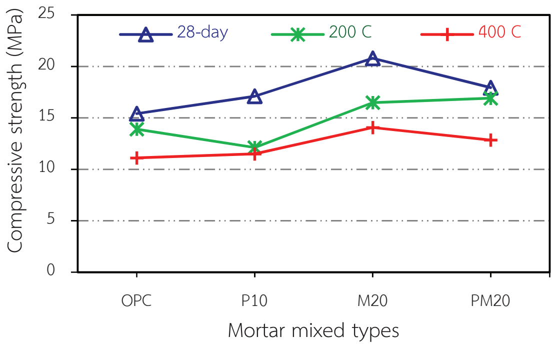

Figure 10 Compressive strength of mortar specimens at elevated temperatures.

OPC specimen has residual compressive strength of 13.90 MPa at 200°C. The M20 and PM20 specimens have residual compressive strength value higher than OPC specimens which are 16.48 and 16.91 MPa, respectively. In addition, the PM20 specimen has the highest residual compressive strength value. In condition of 400 °C, the OPC specimen has residual compressive strength value of 11.11 MPa, and all specimen types have compressive strength value higher than the OPC specimen. Furthermore, M20 specimen has also the highest residual compressive strength value of 14.06 MPa although it is rather high water losing value. It may be a lot of water fills between internal pore spaces of structural bonding. Residual compressive strength of P10 specimen has resembled OPC specimen when both of them are exposed to the temperature of 400°C.

Palm oil fuel ash clinker and metakaolin are pozzolanic materials that can react with $Ca(OH)_2$ to form secondary C-S-H. The $Ca(OH)_2$ caused internal cracking during the increment temperature. The decrement of $Ca(OH)_2$ caused preferable elevated temperatures resistance of the specimens. [19],

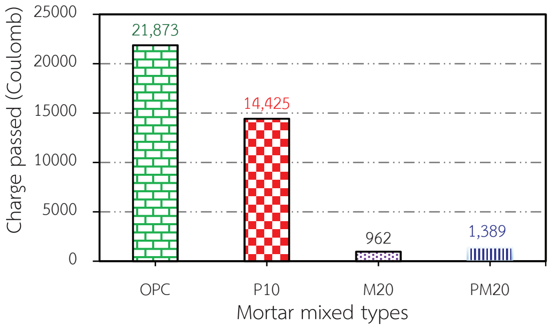

Figure 11 Charge passed of mortar specimens.

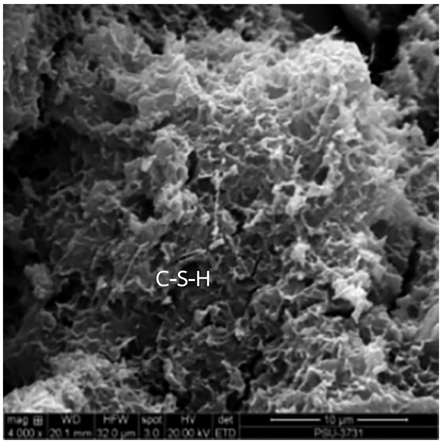

Figure 12 SEM microphotograph of C-S-H in P10 mortar specimens.

[23], [25]. In addition, the M20 specimen was also the highest compressive strength value at 400 °C as shown in Figure 10.

Considering the compressive strength and water losing investigation at elevated temperatures, M20 specimen characterizes superior elevated temperatures resistance than the others. Thermal conductivity measured on M20 and OPC specimens providing 0.581 W/mK and 0.741 W/mK, respectively. Moreover, utilization pumice as aggregate can offer in thermal conductivity value lower than natural sand [10], [26].

3.5 Rapid chloride permeability behavior

Figure 11 shows the total charge passed of OPC specimen obtaining 21,873 coulombs. It is also the highest value. While the charge passed for P10, PM20 and M20 is measured 14,424, 1,389 and 962 coulombs, respectively.

The specimen blended with palm oil fuel ash clinker and metakaolin has a higher resistance of rapid chloride permeability compared with the control specimen. Specially, M20 specimen which has the lowest charge passed. The reaction of $Ca(OH)_2$ and silica caused C-S-H which decreased the porosity of specimens. The reduced porosity resulted in the decrease of the charge passed through the specimens [8], [16], [19].

Using pumice rock as fine aggregate in specimens caused high chloride ion permeability because of high porosity in pumice [27], [28]. The chloride ion passed the specimen blended with metakaolin containing pumice aggregate was provided resemble normal weight concrete contained sand, calcareous stone etc. as aggregate [8], [9].

3.6 Microstructure of specimens

Calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) crystals exposed in various forms. C-S-H often crystallized in the form of honeycomb [29], fibrous [30] etc. In the other side, C-A-H crystal was distinguished in form of platelet [31] and cubic [32]. P10 specimen presents C-S-H crystals distinguish honeycomb form were embedded in matrix under SEM microphotographs magnificemt in Figure 12. It is confirmed as result of hydration and pozzolanic reaction. It is exhibited decreasing porosity and

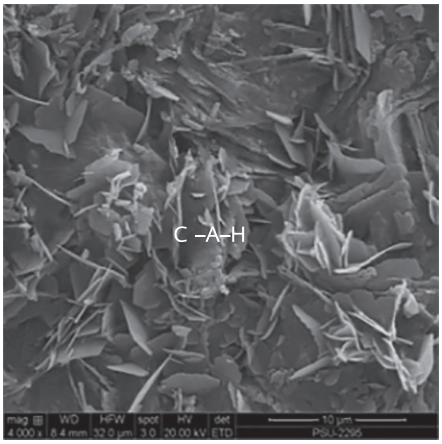

Figure 13 SEM microphotograph of C-A-H in M20 mortar specimens.

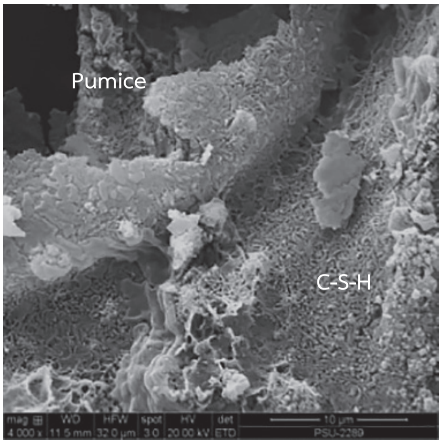

Figure 14 SEM microphotograph of C-S-H at ITZ in PM20 mortar specimens.

compressive strengths increased with also improving elevated temperature and chloride permeability resistance [29]. Likewise, C-A-H crystals were observed in M20 specimen and also filled the pore spaces and improved mechanical performance [18] (Figure 13). PM20 specimen exhibits C-S-H crystal at Interfacial Transition Zone (ITZ) existing around pumice aggregate and matrix (Figure 14) which developed the strength of mortar specimens [10].

4. Conclusions

M20 specimen has the highest compressive strength at ambient and 400 °C. The other P10 and PM20 specimens have superior compressive strength than the control specimen. The appropriate content of metakaolin and palm oil fuel ash clinker improve mechanical performance and physical property. Thermal conductivity indicated that the lightweight aggregate mortar containing pumice blended with palm oil fuel ash clinker and metakaolin can be used as heat insulating material.

Palm oil fuel ash clinker and metakaolin can reduce the alkali-activity especially metakaolin. Pumice aggregate caused high chloride ion permeability but metakaolin can suppress the charges pass of mortar containing pumice aggregate and almost normal weight concrete.

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