The Journal of Applied Science **Vol. 20 No. 1: 39-55 [2021]**
วารสารวิทยาศาสตร์ประยุกต์ doi: 10.14416/j.appsci.2021.01.004
ISSN 1513-7805 Printed in Thailand ISSN 2586-9663 (Online)

Research Article

Sustainable mortar and concrete made from palm oil boiler clinker aggregate comprising rice husk ash and calcium bentonite: Compressive strength and durability assessment

Kamolchanok Kueaket [1] and Danupon Tonnayopas[1*]

[1]Department of Mining and Materials Engineering, Faculty of Engineering, Prince of Songkhla University, Songkhla 90112, Thailand
***E-mail**: danupon.t@psu.ac.th
Received: 04/12/2020; Revised: 25/01/2021; Accepted: 22/03/2021

Abstract

This research was conducted to assess the performances of mortars and concretes made from palm oil boiler clinker aggregate (POBC) blending with rice husk ash (RHA) and calcium bentonite (CB). These blends were used to substitute of ordinary Portland cement (OPC) in the combined proportions of 5wt%CB+5wt%RHA, 5wt%CB+15wt%RHA, 15wt%CB+5wt%RHA, 10wt%CB+20wt%RHA, and 20wt%B+10wt%RHA. The POBC mortars were examined for compressive strength, water absorption, sulfuric acid resistance, and microstructural characterization at the age of 7, 28, and 56 days. Subsequently, the POBC concretes were tested for rapid chloride ion permeability and capillary absorption at 28 and 56 days of curing ages. As a result, the 56-day POBC mortar with the optimum blending of 5% CB and 15% RHA provided the greatest compressive strength of 48 MPa as well as revealed denser microstructure observed under scanning electron microscope (SEM) and greater durability against sulfuric acid attack which surpassed those of the POBC mortar without CB and RHA. Proportionately, the incorporation of 5-10% CB with 15-20% RHA to POBC concrete cured up to 56 days possessed greater durability performances by reducing the chloride ion permeability from moderate to very low ranges as well as lessening capillary absorption. The practical implications of this study are that the POBC could be potentially used in the building sector as a substitute to the conventional aggregates. In addition, the use of CB and RHA could be possibly replaced cement in the optimum proportions without compromising the strength and durability to produce efficiently sustainable POBC mortar and concrete.

Keywords: palm oil boiler clinker, rice husk ash, calcium bentonite, compressive strength, sulfuric acid resistance, chloride ion permeability

Introduction

In 2021 to 2022, the prediction of construction aggregate demand in Asia-Pacific region would be reached to approximately 45,000 million of tonnes (Wiwattananukul et al., 2019). Specifically, the estimate construction aggregate demand in Thailand was 50 million of tonnes annually, and it was predicted to be increased by 20% of each year (Material resources management division, 2019). Conversely, the construction aggregate reserve was approximately 8,010 million of tonnes in Thailand (Innovation in Raw Materials and Primary Industries Division, 2020). Thus, it is apparent that the construction aggregate demand has been inversely

 doi: 10.14416/j.appsci.2021.01.004

proportional to the nonrenewable aggregate reserve. Therefore, the alternative construction aggregate sources should be essentially studied and further brought to use. The demolition waste of construction and industrial waste have been widely applied in the sustainable construction material sectors.

Utilization of local waste materials in construction applications has a great impact on reducing the waste itself, land-fill used, environmental pollutions, and consumption of natural construction materials (Halahla et al., 2019). These impacts also promote sustainable construction towards waste manipulation. To reduce the consumption of the natural construction material and increase the exploitations of waste by-products, the natural aggregate and the cement can be efficiently replaced by the waste by-products such as copper slag (Siddique et al., 2020), granulated blast-furnace slag (Maghool et al., 2020), brick waste (Dang & Zhao, 2019), and fly ash (Chindaprasirt et al., 2020; Klimek et al., 2020; Shakir et al., 2020; Siddique et al., 2020).

Palm oil boiler clinker (POBC) was considered as a rigid solid waste which obtained from local crude palm oil plant. This waste was generated after the combustion of solid palm oil wastes inside boiler and caused the disposal area used and environmental pollutants (Hamada et al., 2020). In regard to the rigid properties and chemical compositions of POBC, the feasibility usages had been studied in term of sustainable construction application as a building material replacements (Shakir et al., 2019). According to Chai et al (2017), POBC can be potentially used as up to 50% of coarse aggregate substitution in size of 4.75-9 mm. Besides, at 100% of POBC coarse aggregate replacement for concrete with w/b ratio of 0.53, the 28-day compressive strength was up to 33 MPa which was only 30% lower than the reference mix made of granite aggregate (Abutaha et al., 2016). Moreover, natural sand can be completely substituted by POBC fine aggregate for eco-mortar production with a minor effect on compressive strength (Kanadasan et al., 2018). The percentage replacement of natural sand by POBC was recommended between 40 to 60% to maintain the mechanical properties (Babalghaith et al., 2020). Although, the studies of using POBC as an aggregate substitution in concrete, asphalt, and geopolymer productions and its mechanical properties have been reported by several researchers , the durability of those composites have not yet been clearly characterized in order to determine the suitability usage and application of POBC. Besides, the study of using 100% of POBC as coarse and fine aggregate with other type of waste as a binder and its durability characteristics have not been reported elsewhere.

Additionally, rice husk ash (RHA) is one of the most useful materials in cement industry. Several important roles of RHA as a pozzolan in cementitious material had been revealed, it could reduce the capillary pore and promote long term compressive strength of concrete, especially, for the low carbon RHA (Kang et al., 2019; Sandhu & Siddique, 2017). The pozzolanic activity was promoted by the addition of RHA which resulted in the micro-filler effect that filled up the capillary pore of cement matrix by the production of calcium silicate hydrate gels (C-S-H gels) (Gill & Siddique, 2018). Besides, the efficiency of using RHA as a cement replacement on acid resistance was also found that concrete incorporating RHA performed the superior resistance due to the pozzolanic activity consumed calcium hydroxide (CH) content and strengthened the bond between different phases in microstructure by producing more C-S-H (Koushkbaghi et al., 2019). Conversely, the large amount of RHA replacement in concrete can be decreased the compressive strength (Umasabor & Okovido, 2018).

Furthermore, calcium bentonite (CB) was addressed for a natural pozzolan (Memon et al., 2012). The Pakistani bentonite or CB was partially replaced by weight of cement and found that the compressive strength of 56-day mortar containing 12-15% CB as a cement replacement can reach approximately 30 MPa, which was significantly 2.7% higher than that of without adding

CB. The pore filling effect of using up to 10% CB replaced by weight of cement was achieved in mortar cured up to 28 days. This effect established the particle packing improvement and a decrease in water absorption due to the very-fine grain particles of CB (Ahmad et al., 2011).

This research aims to utilize the local waste by-products and evaluate the performances of mortars and concretes containing POBC aggregate with the combination of RHA and CB as a cement replacements. The compressive strength, water absorption, and sulfuric acid (H_2SO_4) resistance of POBC mortars were carried out at the age of 7, 28, and 56 days. In addition, the POBC concretes cured at 28 and 56 days were determined for rapid chloride ion permeability and 72-hour capillary absorption. Accordingly, the microstructures of POBC mortar containing CB and RHA blends were characterized via scanning electron microscope (SEM).

Materials and methods

Ordinary Portland cement (OPC) as per ASTM C150 was used in this study. POBC was collected from disposal area of oil palm plant at Surat Thani province, as received POBC was displayed in Figure 1a. The POBC was washed, dried, and crushed with jaw crusher to achieve the POBC coarse aggregate (POBCCA) and gyratory crusher to achieve the POBC fine aggregate (POBCFA), as depicted in Figure 1b-c. The enlargement of the POBC mortar's cross-section obtained from stereo microscope is shown in Figure 1d. The mineralogical characteristics of POBC were characterized via X-ray diffraction (XRD) analysis, as shown in Figure 2. The mineral compositions of POBC consisted of whitlockite, diopside, and three polymorphs of SiO_2, which were quartz, tridymite, and crystobalite. The green color of POBC can be accounted for the mineral composition of diopside. The properties of POBC aggregates were listed in Table 1. Conforming to ASTM C131 (2020) and BS 182-112 (1990), the POBCCA is not recommended for using in road surfacing, structural works, or heavy duty constructions due to the lower resistance to crushing and abrasion. In addition, CB was purchased from supplier (product of Thailand), as seen in Figure 1b.

RHA was obtained after the open air burning of using rice husk as a biomass fuel in Phatthalung province. Then, it was calcined with an electrical furnace at 700 °C for 1 hour (HR: 5 °C/min) in order to reduce the contaminated organic matters or unburned carbon. After calcining process, RHA was ground with jar mill at rotation speed of 65 revolution per minute for 12 hours to meet the requirement of ASTM C618 (2019). The chemical compositions and particle size of CB and RHA were analyzed via wavelength dispersive X-ray fluorescence spectrophotometer (WDXRF) and laser particle size analyzer (LPSA), as tabulated in Table 2. The XRD pattern of RHA is depicted in Figure 3. The RHA composed of few crystalline phase of crystobalite and quartz, mostly contained amorphous silica, which confirmed by the broad hump peak between 2Θ of 15° to 25° and other wide range of low intensity peaks, as presented in the dashed line circle. The particle size distributions of the binders and aggregates used are shown in Figure 4.

doi: 10.14416/j.appsci.2021.01.004

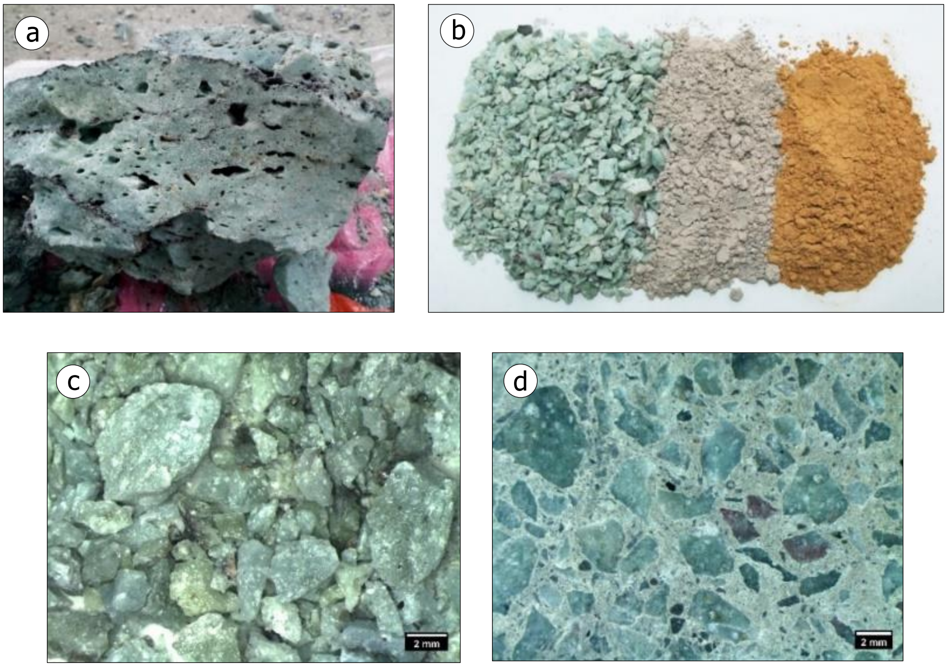

Figure 1 As received POBC (a), from left to right: crushed POBC as a fine aggregate, rice husk ash, and calcium bentonite (b), enlargement of POBC fine aggregate (c), and cross-section of mortar made of POBC fine aggregate (d)

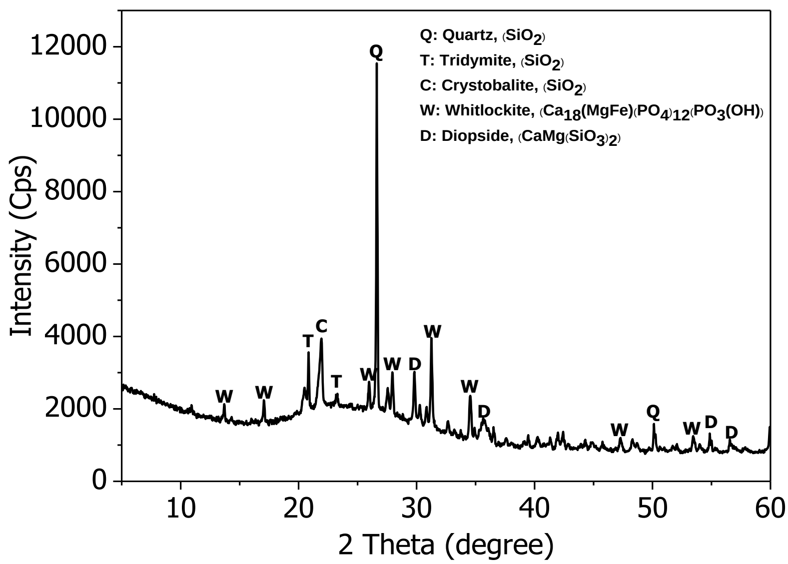

Figure 2 XRD pattern and phase compositions of POBC

Vol. 20 No. 1: 39-55 [2021]
doi: 10.14416/j.appsci.2021.01.004

Table 1 The physical properties of POBC aggregates

Properties	POBCCA	POBCFA
Organic impurity (ASTM C40, 2020)	None	
24-hour water absorption (%)	2.80	3.10
Specific gravity	2.28	2.40
Unit weight (kg/m^3)	1,182	1,350
Fineness modulus	5.30	3.70
Aggregate impact value (%)	36	-
Los Angles abrasion (%)	38	-

Table 2. The chemical and physical properties of CB and RHA

	CB	RHA
Chemical compositions		
SiO_2 (%)	56.62	93.93
Fe_2O_3 (%)	0.02	0.36
Al_2O_3 (%)	19.81	0.33
SO_3 (%)	0.69	0.21
SiO_2+ Fe_2O_3+ Al_2O_3 (%)	76.45	94.62
Loss on ignition (%)	10.12	0.67
Physical properties		
D_{10} (μm)	0.6	2.3
D_{50} (μm)	2.3	12.5
D_{90} (μm)	14.2	38.6
D[4,3] (μm)	5.5	16.5

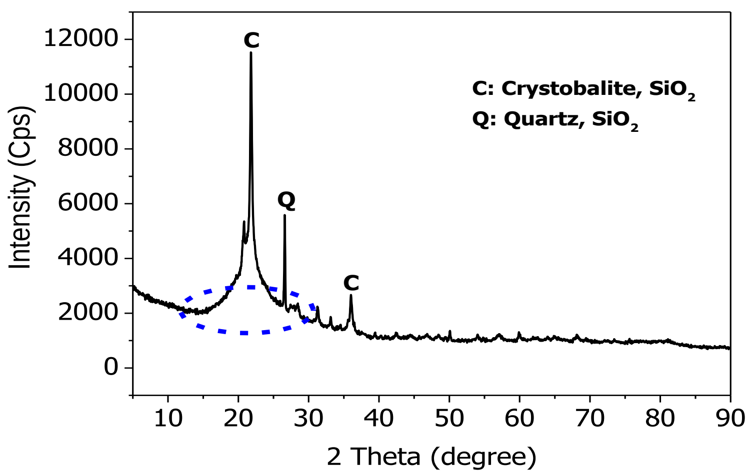

Figure 3 XRD pattern and phase compositions of RHA

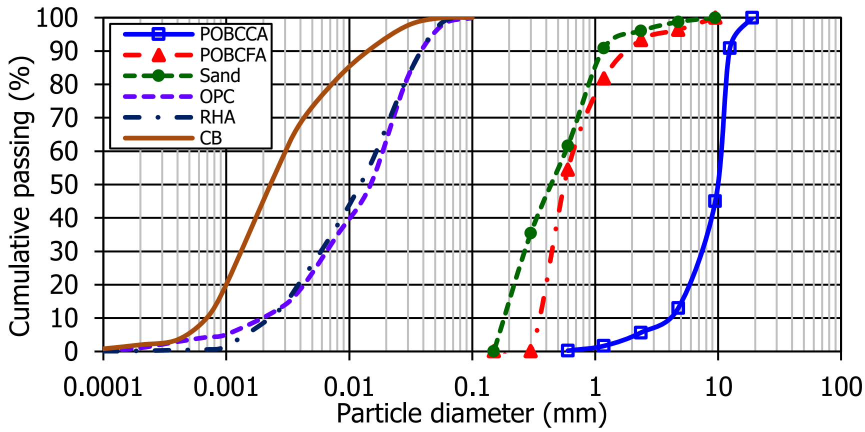

Figure 4 Particle size distribution of POBC aggregates and binders

Mix designation

Mix designations of POBC mortar and concrete were done complying with ASTM C109 (2016), ASTM C192 (2019), and ACI 211.1 (1991). For both of POBC mortar and concrete, the blending of RHA and CB partially replaced by weight of OPC, as followed in Table 3. For example, the mix designation B5R5 was the combination between 5% CB and 5% RHA replaced by weight of OPC. The POBC mortar specimen was taken for determine the compressive strength, water absorption, and resistance to sulfuric acid (H_2SO_4) attack. The POBC concrete specimen was taken for determine the rapid chloride permeability and capillary absorption. For the POBC mortar mix designations, 50-mm cube specimens were casted with the binder to aggregate ratio of 1:2.75 and water to binder ratio of 0.48. The percentage flow of fresh mortar was determined as per ASTM C1437 (2015). Then, the hardened mortar specimens were cured in saturated lime water at ambient temperature (25±5°C) with 80-85% relative humidity for 7, 28, and 56 days. For the POBC concrete mix designations, 100 mm diameter with 50 mm length concrete discs were prepared by using natural sand (F.M 3.15), POBCCA with maximum size of 10 mm (F.M. 5.31), and taken water to binder ratio of 0.48. The concrete specimens were cured in the same condition of POBC mortar for 28 and 56 days.

Table 3 The mix designations of POBC mortar for various combination ratios of RHA and CB

Mix designations	Mix proportions									
	POBC mortar					POBC concrete				
	Binder (kg/m^3)			POBCFA (kg/m^3)	Flow (%)	Binder (kg/m^3)			Sand (kg/m^3)	POBCCA (kg/m^3)
	OPC	CB	RHA			OPC	CB	RHA		
Control	500	0	0	1,375	121	500	0	0	1,175	765
B5R5	450	25	25	1,375	119	450	25	25	1,175	765
B5R15	400	25	75	1,375	108	400	25	75	1,175	765
B15R5	400	75	25	1,375	112	400	75	25	1,175	765
B10R20	350	50	100	1,375	101	350	50	100	1,175	765
B20R10	350	100	50	1,375	103	350	100	50	1,175	765

 doi: 10.14416/j.appsci.2021.01.004

Test procedures

The compressive strength and water absorption of POBC mortar were prepared and tested in accordance with ASTM C109 (2019) and ASTM C373 (2014). The strength activity index was determined according to ASTM C618 (2019). Resistance to 0.005 M sulfuric acid attack (pH=2.5) was measured by the comparison between the weight and compressive strength of POBC mortars before exposure and after exposure to sulfuric acid solution at particular curing ages. The sulfuric acid was renewed every week in order to maintain the pH value of the solution. The sulfuric acid resistance test was conducted for 6 weeks. The rapid chloride permeability test and capillary absorption test of POBC concretes were performed conforming to ASTM C1202 (2019) and ASTM C1585 (2020). The tests set up of the rapid chloride ion permeability and the capillary absorption are presented in Figure 5. For the microstructural characterization, the POBC mortars cured at 56 days were investigated using scanning electron microscope (SEM) at the accelerate voltage of 20 kV.

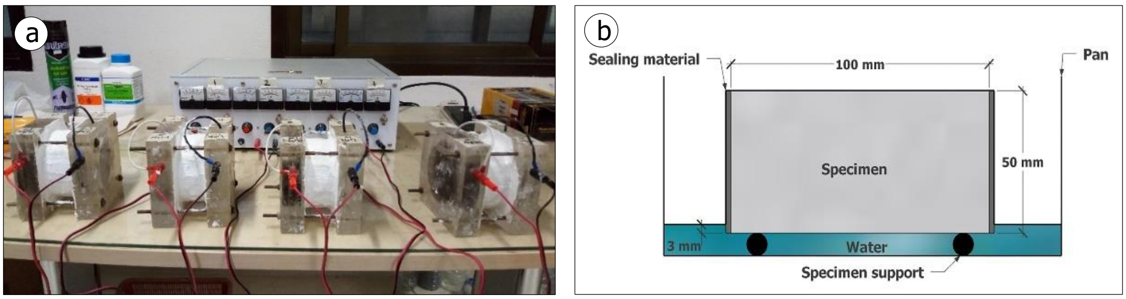

Figure 5 Schematics of rapid chloride permeability (a) and capillary absorption test (b) configurations

Results and discussion

1. Compressive strength

The compressive strength of mortar specimens cured in saturated lime water for a period of 7, 28, and 56 days are shown in Figure 6. Overall, the compressive strength of all mix designations was increased with curing ages. It can be observed that the compressive strength of mix designations B10R20 and B5R15 were equivalent to or higher than that of the control mix at the age of 28 and 56 days. Particularly, the highest 56-day compressive strength of 48 MPa was found in the mix B5R15, which was greater than that of the control mix by 7%. However, a reduction in 56-day compressive strength was found in the mix B5R5, B15R5, and B20R10. Which was lesser than that of the control mix by 11%, 16%, and 15%, respectively. According to these results, it can be seen that the mix designations containing more RHA/CB ratios (B5R15 and B10R20) and taken up to 28-day curing ages could be maintained and provided the development of the compressive strength in comparison to the control mix, B5R5, B15R5, and B20R10. These compressive strength results comply with those of (Joshaghani & Moeini, 2018). Who reported that the compressive strength of 90-day mortar containing 15% RHA was 6% greater than that of the mixture without RHA. Additionally, the compressive strength of 28-day mortar specimen containing 6% bentonite was higher than that of the control specimen by 3% (Memon et al., 2012). However, the effects of hybrid mixes between RHA and CB have not been studied and reported elsewhere. Therefore, according to the compressive strength results of this study, the mix designation B5R15 and B10R20 can be recommended as the optimum CB/RHA ratios for using as an OPC replacement without detrimental to the compressive strength.

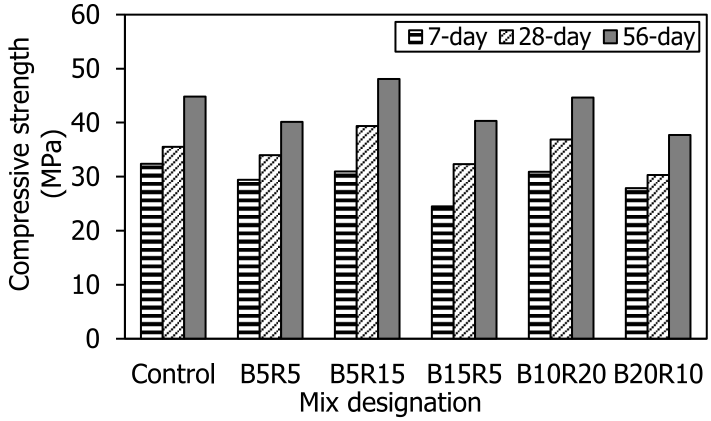

Figure 6 Compressive strengths of POBC mortars with different mix designations at the age of 7, 28, 56 days

2. Strength activity index

The strength activity index (SAI) of all mix designations is demonstrated in Figure 7. The determination of SAI is to indicate that the SCMs or any tested materials have the pozzolanic properties. According to ASTM C618 (2019), the requirement of SAI is considered as more than 75%. For the mixture containing the hybrid mixes of RHA and CB, the SAI values of those mix designations were in the range of 76-111%. In addition, the SAI of those mixes were meet the standard requirement and significantly increased with ages. In addition, the highest SAI was found in the mix B5R15 at the age of 28 days. This finding is in line with Man et al. (2019) and Rehman et al. (2020). The development of SAI and compressive strength could be due to the chemical compositions of RHA and CB. Which mainly consisted of silica (SiO_2). Moreover, the amount of SiO_2+ Fe_2O_3+ Al_2O_3 contents were more than 70%. Thus, the active silica could be reacted with $Ca(OH)_2$ and promote and pozzolanic reaction's products caused the improvement in compressive strength (Man et al., 2019; Rehman et al., 2020).

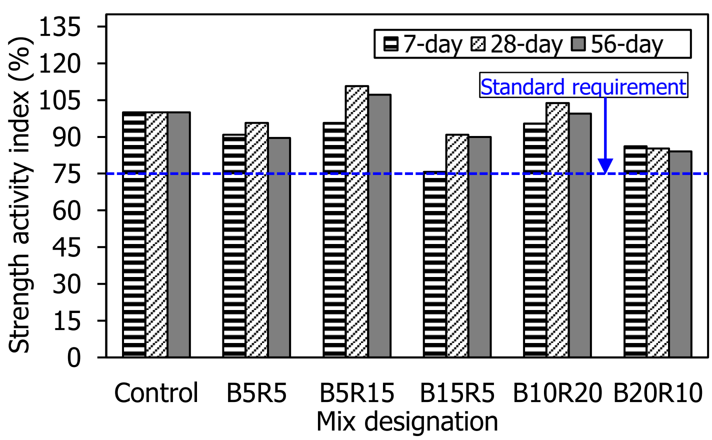

Figure 7 Strength activity index of POBC mortars with different mix designations at the age of 7, 28, 56 days

 doi: 10.14416/j.appsci.2021.01.004

3. Water absorption

The water absorption of different mix designations at the ages of 7, 28, and 56 days is shown in Figure 8. The water absorption of all mix designations was decreased with prolonged curing ages. Meanwhile, at the early age of curing, the water absorption of the hybrid mix designations was similar to the control mix. At the age of 28 and 56 days, the percentage of water absorption was decreased by 15 to 26% for the mix B5R5, B5R15, and B10R20, when compared to that of the control mix. The lowest percentage of water absorption was found in the mix B5R15 at the age of 28 and 56 days, which was 26% lesser than the control mix. Jamil et al. (2016) pointed out that the filler effect and secondary C-S-H products from pozzolanic reaction of RHA filled up the pore space in the cement matrix and caused the reduction in the water absorption. Furthermore, the reduction in the water absorption was also found in the specimen containing up to 10% bentonite. This is due to the micro-filling effect of very fine-grain bentonite that can improve the particle packing of binder and reduce the water to binder ratio (Ahmad et al., 2011; Mesboua et al., 2018). However, an adverse effect of more bentonite contents could be attributed to the unreacted bentonite particles within the cement matrix absorbed more water, thus the water absorption of specimen containing more bentonite increased (Ahmad et al., 2011).

Although, the control mix revealed the highest 56-day water absorption while provided the greater compressive strength than the mix designation B5R5, B15R5, and B20R10. This could be due to the complex mechanism between RHA and CB, which contributed greatly to both of the pozzolanic reaction and filler effect. For the mechanism of RHA, the very-fine grain particle substantially improved pore size, reduced water absorption, and was ineffective to the strength development due to the pozzolanic reaction takes place in prolonged curing period. Moreover, this mechanism was confirmed by Bheel et al. (2020) that an increase in dosage of RHA replacement decreased the water absorption, whereas only the optimized 5% of RHA increased the compressive strength at the age of 28 days. Correspondingly, the significance mechanism of CB is pore refinement and improving the impermeability of cement matrix (Masood et al., 2020; Rehman et al., 2019). Liu et al. (2020) also concluded that the incorporating 10% CB developed the durability by filling effect and only the C-S-H gel formed on the surface of the specimen, whereas the strength development index need to be included (i) the forming of ettringite and (ii) the overlapping of hydration product on the specimen's surface.

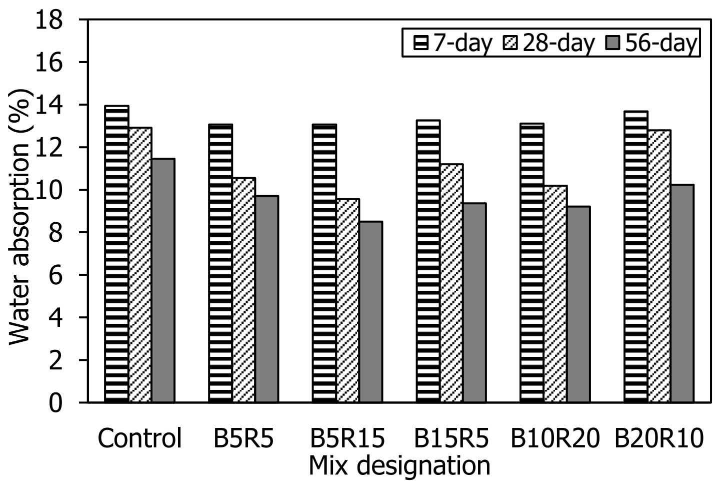

Figure 8 Water absorption of POBC mortars with different mix designations at the age of 7, 28, 56 days

 doi: 10.14416/j.appsci.2021.01.004

4. Resistance to sulfuric acid attack

Weight loss

The weight loss of mortars at different curing ages exposed to 0.005 M sulfuric acid solution for 42 days is shown in Figure 9. It can be observed that the weight loss of all mix designations was decreased with curing age before exposure to sulfuric acid solution. At the later age, 56 days of curing, the ranges of weight loss for all hybrid mix designations were lesser than the control mix. Which were in the range of 1 to 44%. Especially, for the mix containing more combination ratio of RHA/CB (B10R20 and B5R15), the weight loss was up to 41 and 44% lower than that of the control mix. This is mainly attributed to (i) the less water absorption and (ii) the pozzolanic activity from the silica compositions of RHA (94% SiO_2) was greater than CB (57% SiO_2) which contributed to an increase in C-S-H forming and resulted in more impermeable matrix. Thus, the more durability was obtained in the mix containing more RHA contents (Ahmad et al., 2011). Correspondingly, the mix designation B5R15 showed a lesser surface erosion than that of the control mix, as shown in Figure 10. Min & Song (2018) also reported that the crucial corrosion can be indicated in the yellow color area that appeared on the exposed surface of the cement composite to sulfuric acid solution.

Compressive strength loss

The compressive strength loss of mortars exposed to 0.005 M sulfuric acid solution is shown in Figure 11. After 42 days of exposure, the compressive strength loss is seen in all mix designations. In accordance with the weight loss results, a similar trend was observed in the compressive strength loss. An increase in curing ages before sulfuric acid attack and the more RHA/CB ratios decreased the loss in compressive strength. The lowest compressive strength loss was found in the mix B5R15 at the age of 56 days. Which was 18 % lower than that of the control mix. This finding suggests that up to 20% of OPC can be replaced by the combination blend of CB and RHA at the optimum CB/RHA ratio as in the mix designation B5R15, which produced the development both in the compressive strength and durability.

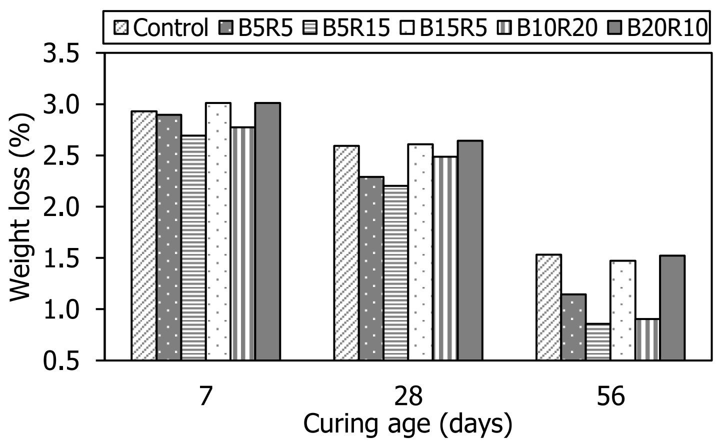

Figure 9 Weight loss of POBC mortars with different mix designations cured at 7, 28, and 56 days exposed to 0.005 M sulfuric acid solution for 42 days

 doi: 10.14416/j.appsci.2021.01.004

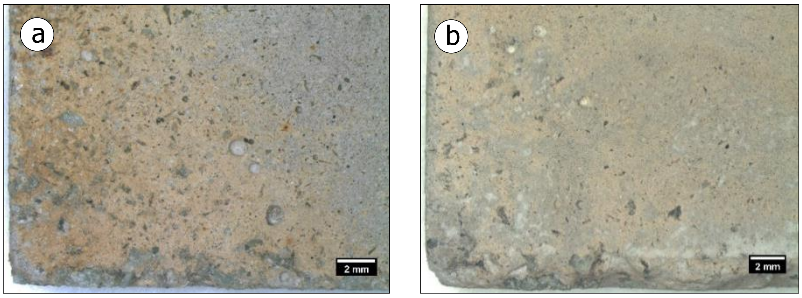

Figure 10 Enlargement of the surface of 56-day mortars: control mix (a) and mix designation B5R15 (b) after exposed to 0.005 M sulfuric acid solution for 42 days

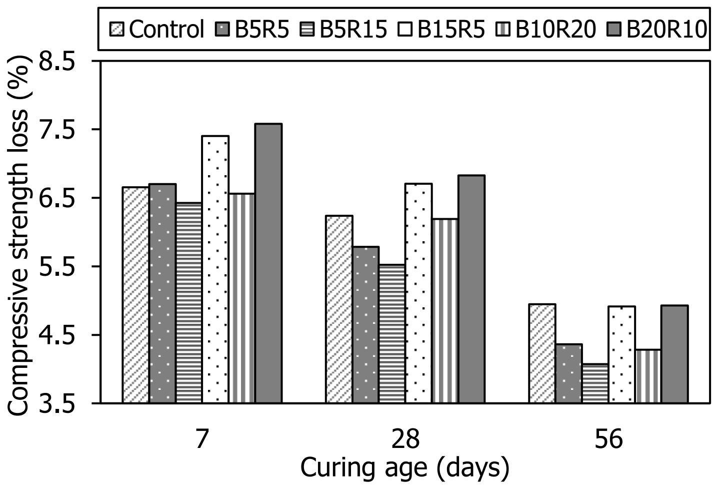

Figure 11 Compressive strength loss of POBC mortars with different mix designations cured at 7, 28, and 56 days exposed to 0.005 M sulfuric acid solution for 42 days

5. Rapid chloride permeability and capillary absorption

The total charge passed and capillary absorption of different mix designations and curing ages are given in Figure 12. According to ASTM C1202 (2019), the qualitative indication of chloride ion permeability of any concrete specimen was determined as followed: the total charges passed of concrete specimens that fall in the range of (i) >4,000 coulombs, (ii) 2,000-4,000 coulombs, (iii) 1,000-2,000 coulombs, and (iv) 100-1,000 coulombs were considered as high permeability, moderate permeability, low permeability, and very low permeability, respectively. A decrease in chloride ion permeability was observed in all hybrid mixes with prolonged curing ages. As compared to the control mix, the decrease was in the range of 4-77% and 30-78% at the age of 28 and 56 days, respectively. At the age of 56 days, the chloride ion permeability of the mix designations B5R15 and B10R20 was in very low ranges. For the mix designations B5R5, B15R5, and B20R10 cured at 56 days, the chloride ion permeability was in the low range, whereas the chloride ion permeability of the control mix was in the moderate range. Consequently, the capillary absorption results corresponded to the chloride ion permeability. An increase in curing ages decrease capillary absorption. The significant reduction in the 72-hour capillary absorption was found in the mix designations B5R15 and B10R20 at the age of 56 days, which were lower than the control mix by 44% and 56%, respectively. It can be seen that the chloride permeability and the capillary absorption decreased with an increase in curing ages and RHA/CB ratios, as was found in mixture designations B5R15 and B10R20. Ganesan et al. (2008) also found that the chloride permeability and rate of capillary absorption had a good relationship due to the reduction of permeable voids in matrix by the pozzolanic activity of RHA as an additive and the prolonged curing ages. This finding also in agreement with those of Huang et al. (2017), Laidani et al. (2020), and Zareei et al. (2017) that the capillary absorption and chloride ion penetration of concrete specimen containing RHA were reduced by an increase in the RHA content, while only adding up to 10% bentonite could reduce the capillary absorption. Moreover, an increase in RHA content up to 20% reduced the 72-hour capillary absorption by 15%, compared to the specimen without RHA (Zahedi et al., 2015).

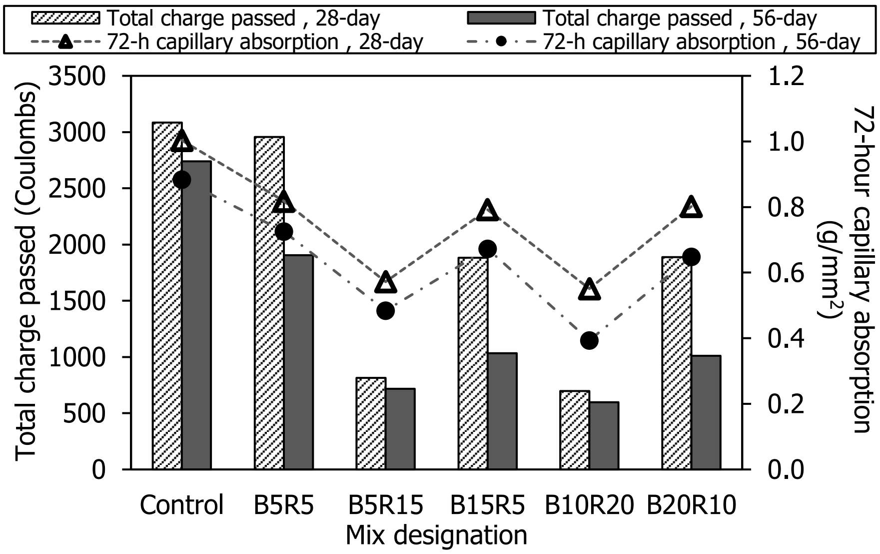

Figure 12 The chloride ion permeability and 72-hour capillary absorption of POBC concrete with different mix designations at the age of 28 and 56 days

6. Microstructural characterization

The SEM images are demonstrated the comparison between OPC particles and combination blends of OPC, RHA, and CB particles of the mix designation B5R15 as shown in Figure 13a-b. It can be seen that the different in particle sizes among OPC, RHA, and CB played the important role in increasing the particle packing of the binder. An increase in particle packing was observed in the binder of the mix designation B5R15 in comparison to the pure OPC particles. Accordingly, the very fine micro-particles of CB and rounded agglomerate RHA particles also contributed to the reduction in water content of the binder due to RHA and CB absorbed more water (Ahmad et al., 2011; Mesboua et al., 2018). The SEM images of the hardened pastes of the control mix and mix designation B5R15 are illustrated in Figure 13c-d. It can be clearly seen that the hydration's products were found in both mix designations. Particularly, the mix designation B5R15 manifested denser matrix and lower micro-pore spaces when compared to the control mix. The dense flocs-like C-S-H was obviously found in the groundmass of the mix designation B5R15 and the micro-pore spaces were reduced by the spreading of the dense C-S-H framework. For the matrix of the control mix, the loosely fibrous-like and flocs-like C-S-H were found. The more C-S-H embedded in the mix containing RHA and CB could be due to the pozzolanic activity that consumed free $Ca(OH)_2$ from both of hydration and pozzolanic reaction's products, then produced more C-S-H (Chopra et al., 2015; Masood et al., 2020). Besides, the denser microstructure could be attributed to the development in compressive strength, the reduction in water absorption, and the durability improvement of the mix designation B5R15 in comparison to the control mix. The morphology of C-S-H observed from SEM images of this study was characterized and compared to the flocs-like C-S-H found by Yu et al. (1999), Cizer et al. (2007), and the fibrous-like C-S-H found by El-gama et al. (2018). However, the characteristics of C-S-H can be shown in various forms depended on the curing condition, additive used, water to binder ratios, and designation of mixture (Cizer et al., 2007; Shen et al., 2019).

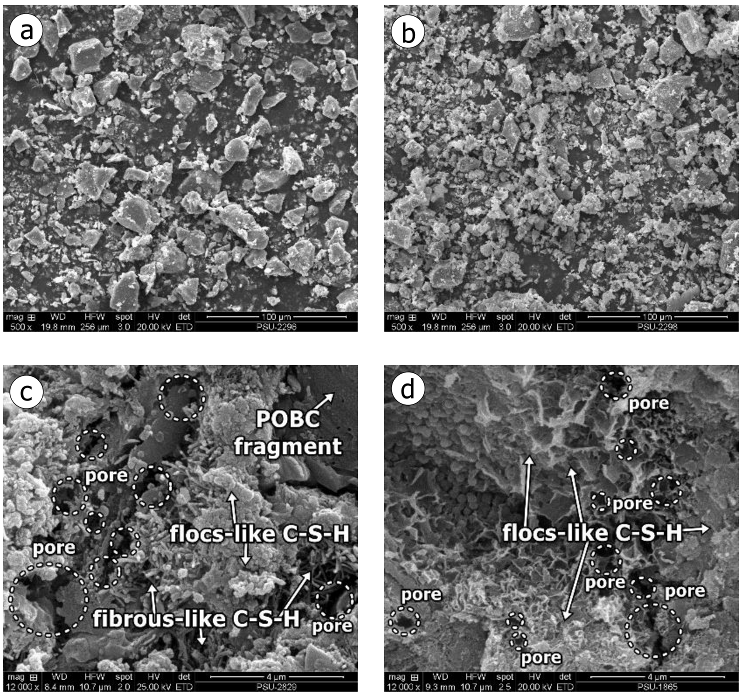

Figure 13 SEM images of OPC particles (a), blends consisted of OPC, CB, and RHA particles of mix designation B5R15 (b), the hardened paste cured at 56 days of the control mix (c), and the mix designation B5R15 (d)

Conclusion

Based on this study results, the conclusions can be provided as following:

(1) The POBC mortar with the optimum combination of 5% of CB and 15% of RHA replaced by weight of OPC (mix designation B5R15) developed the superior performance at the curing age up to 56 days when compared to the control and the others mix designations. Moreover, the mix designation B5R15 provided the highest compressive strength, the lowest water absorption, and the lowest weight and compressive strength loss due to sulfuric acid attack.

(2) The chloride ion permeability and capillary absorption decreased with an increase in RHA combination ratios and curing ages. The very low range of chloride ion permeability belonged

to the mix designation B5R15 and B10R20 cured at 56 days. However, the chloride ion permeability of the others mix designations were fallen into the low range except for the control mix that was continually fallen in the moderate range when the curing ages increased. The optimum combination of 5-10% of CB and 15-20% of RHA replaced by weight of OPC would be recommended for the chloride ion permeability resistance of the POBC concrete.

(3) According to the microstructure characterization using SEM images, the denser matrix occupied by C-S-H framework and lower pore spaces of the mix designation B5R15 in comparison to the control mix contributed to the compressive strength and durability improvement.

(4) Regarding to this investigation, the POBC can be used as an aggregate substitution for producing conventional mortars and concretes in non-structural construction work. The optimum combinations of CB and RHA for POBC mortars and concretes could help diminishing the cement used and promoting the durability performance.

Acknowledgements

The authors expressed the deepest gratitude to PSU Graduate School and Faculty of Engineering, Prince of Songkla University for the partially financial supports and Graduate Engineering Scholarship.

References

Abutaha, F., Abdul Razak, H., & Kanadasan, J. (2016). Effect of palm oil clinker (POC) aggregates on fresh and hardened properties of concrete. *Construction and Building Materials, 112*, 416-423. https://doi.org/10.1016/j.conbuildmat.2016.02.172

Ahmad, S., Barbhuiya, S. A., Elahi, A., & Iqbal, J. (2011). Effect of Pakistani bentonite on properties of mortar and concrete. *Clay Minerals, 46*(1), 85-92. https:// doi.org/10.1180/claymin.2011.046.1.85

Standard, A. C. I. (1996). Standard practice for selecting proportions for normal, heavyweight, and mass concrete. *ACI Man. Concr. Pract*, 1-38.

ASTM. (2014). *Standard test method for water absorption, bulk density, apparent porosity, and apparent specific gravity of fired whiteware products, ceramic tiles, and glass tiles* (ASTM C373-14). US: ASTM International. https://compass.astm.org/document/?contentCode=ASTM%7CC037314%7CenUS&proxycl=https%3A%2F%2Fsecure.astm.org&fromLogin=true

ASTM. (2020). *Standard test method for flow of hydraulic cement mortar* (ASTM C1437-15). US: ASTM International. https://compass.astm.org/document/?contentCode=ASTM%7CC1437-15%7CenUS&proxycl=https%3A%2F%2Fsecure.astm.org&fromLogin=true

ASTM. (2016). *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) (ASTM* C109/C109M-16a) . https://www.astm.org/c0109_c0109m-16.html

ASTM. (2019). *Standard Specification for Portland Cement* (ASTM C150/C150M-19a). US: ASTM International. https://www.astm.org/c0150_c0150m-22.html

ASTM. (2012).*Practice for Making and Curing Concrete Test Specimens in the Laboratory* (ASTM C192/C192M-19) *. US:* ASTM International. https://www.astm.org/c0192_c0192m-07.html

ASTM. (2012). *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete* (ASTM Standard C618). US: ASTM International. https://global.ihs.com/doc_detail.cfm?document_name=ASTM%20C618&item_s_key=00014875

ASTM. (1997). 1202: Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. *Annual book of ASTM standards*, *4*(2), 639-644. https://www.astm.org/c1437-20.html

ASTM. (2020). *Standard Test Method for Organic Impurities in Fine Aggregates for Concrete* (ASTM C40/C40M-20). US: ASTM International. https://www.astm.org/c1437-20.html

ASTM. (2020). *Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes* (ASTM C1585-20). US: ASTM International .https://www.astm.org/c1585-20.html

ASTM. (2020). *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine* (ASTM C131/C131M-20). US: ASTM International. https://www.astm.org/c1437-20.html

Babalghaith, A. M., Koting, S., Sulong, N. H. R., Karim, M. R., & AlMashjary, B. M. (2020). Performance evaluation of stone mastic asphalt (SMA) mixtures with palm oil clinker (POC) as fine aggregate replacement. *Construction and Building Materials, 262*, 11. https://doi.org/10.1016/j.conbuildmat.2020.120546

Bheel, N., Keerio, M. A., Kumar, A., Shahzaib, J., Ali, Z., Ali, M., & Sohu, S. (2020). An investigation on fresh and hardened properties of concrete blended with rice husk ash as cementitious ingredient and coal bottom ash as sand replacement material. *Silicon*, 12. https://doi.org/10.1007/s12633-020-00906-3

British Standards Institute. (1990). *BS 812-112: Methods for determination of aggregate impact value (AIV)*. https://www.en-standard.eu/search/?q=BS812-112

Chai, L. J., Shafigh, P., Mahmud, H., & Aslam, M. (2017). Effect of substitution of normal weight coarse aggregate with oil-palm-boiler clinker on properties of concrete. *Sains Malaysiana, 46*(4), 645-653. https://doi.org/10.17576/jsm-2017-4604-18

Chindaprasirt, P., Kasemsiri, P., Leekongbub, S., & Posi, P. (2020). Durability of concrete containing recycled asphaltic concrete aggregate and high calcium fly ash. *International Journal of Geomate, 19*(74), 8-14. https://doi.org/10.21660/2020.74.5541

Chopra, D., Siddique, R., & Kunal. (2015). Strength, permeability and microstructure of self-compacting concrete containing rice husk ash. *Biosystems Engineering, 130*, 72-80. https://doi.org/10.1016/j.biosystemseng.2014.12.005

Cizer, O., Van Balen, K., Van Gemert, D., & Elsen, J. (2007). *Carbonation and hydration of mortars with calcium hydroxide and calcium silicate binders* [Paper presentation]. International Conference on Sustainable Construction Materials and Technologies.

Dang, J. T., & Zhao, J. (2019). Influence of waste clay bricks as fine aggregate on the mechanical and microstructural properties of concrete. *Construction and Building Materials*, *228*, 9. https://doi.org/10.1016/j.conbuildmat.2019.116757

El-Gamal, S. M. A., Abo-El-Enein, S. A., El-Hosiny, F. I., Amin, M. S., & Ramadan, M. (2018). Thermal resistance, microstructure and mechanical properties of type I Portland cement pastes containing low-cost nanoparticles. *Journal of Thermal Analysis and Calorimetry*, *131*(2), 949-968. https://doi.org/10.1007/s10973-017-6629-1

Ganesan, K., Rajagopal, K., & Thangavel, K. (2008). Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete. *Construction and Building Materials, 22*(8), 1675-1683. https://doi.org/10.1016/j.conbuildmat.2007.06.011

Gill, A. S., & Siddique, R. (2018). Durability properties of self-compacting concrete incorporating metakaolin and rice husk ash. *Construction and Building Materials, 176*, 323-332. https://doi.org/10.1016/j.conbuildmat.2018.05.054

Halahla, A. M., Akhtar, M., & Almasri, A. H. (2019). Utilization of Demolished Waste as Coarse Aggregate in Concrete. *Civil Engineering Journal-Tehran, 5*(3), 540-551. https://doi.org/10.28991/cej-2019-03091266

Hamada, H. M., Jokhio, G. A., Al-Attar, A. A., Yahaya, F. M., Muthusamy, K., Humada, A. M., & Gul, Y. (2020). The use of palm oil clinker as a sustainable construction material: A review. *Cement & Concrete Composites, 106*, 19. https://doi.org/10.1016/j.cemconcomp.2019.103447

Huang, H., Gao, X., Wang, H., & Ye, H. (2017). Influence of rice husk ash on strength and permeability of ultra-high performance concrete. *Construction and Building Materials, 149*, 621-628. https://doi.org/10.1016/j.conbuildmat.2017.05.155

Innovation in Raw Materials and Primary Industries Division. (2020). *Construction aggregate reserve in Thailand*. http://www.dpim.go.th/qry-stones/quarry3.php

Jamil, M., Khan, M. N. N., Karim, M. R., Kaish, A. B. M. A., & Zain, M. F. M. (2016). Physical and chemical contributions of rice husk ash on the properties of mortar. *Construction and Building Materials, 128*, 185-198. https://doi.org/10.1016/j.conbuildmat.2016.10.029

Joshaghani, A., & Moeini, M. A. (2018). Evaluating the effects of sugarcane-bagasse ash and rice-husk ash on the mechanical and durability properties of mortar. *Journal of Materials in Civil Engineering, 30*(7), 14. https://doi.org/10.1061/(asce)mt.1943-5533.0002317

Kanadasan, J., Razak, H. A., & Subramaniam, V. (2018). Properties of high flowable mortar containing high volume palm oil clinker (POC) fine for eco-friendly construction. *Journal of Cleaner Production, 170*, 1244-1259. https://doi.org/10.1016/j.jclepro.2017.09.068

Kang, S.-H., Hong, S.-G., & Moon, J. (2019). The use of rice husk ash as reactive filler in ultra-high performance concrete. *Cement and Concrete Research, 115*, 389-400. https://doi.org/10.1016/j.cemconres.2018.09.004

Koushkbaghi, M., Kazemi, M. J., Mosavi, H., & Mohseni, E. (2019). Acid resistance and durability properties of steel fiber-reinforced concrete incorporating rice husk ash and recycled aggregate. *Construction and Building Materials, 202*, 266-275. https://doi.org/10.1016/j.conbuildmat.2018.12.224

Laidani, Z. E., Benabed, B., Abousnina, R., Gueddouda, M. K., & Khatib, M. J. (2020). Potential pozzolanicity of Algerian calcined bentonite used as cement replacement: optimisation of calcination temperature and effect on strength of self-compacting mortars. *European Journal of Environmental and Civil Engineering*, 23. https://doi.org/10.1080/19648189.2020.1713898

Liu, M. L., Hu, Y., Lai, Z. Y., Yan, T., He, X., Wu, J., Lv,& S. Z. (2020). Influence of various bentonites on the mechanical properties and impermeability of cement mortars. *Construction and Building Materials, 241*, 12. https://doi.org/10.1016/j.conbuildmat.2020.118015

Maghool, F., Arulrajah, A., Horpibulsuk, S., & Mohajerani, A. (2020). Engineering and leachate characteristics of granulated blast-furnace slag as a construction material. *Journal of Materials in Civil Engineering*, *32*(7), 10. https://doi.org/:10.1061/(asce)mt.1943-5533.0003212

Man, X. Y., Haque, M. A., & Chen, B. (2019). Engineering properties and microstructure analysis of magnesium phosphate cement mortar containing bentonite clay. *Construction and Building Materials, 227*. https://doi.org/10.1016/j.conbuildmat.2019.08.037

Masood, B., Elahi, A., Barbhuiya, S., & Ali, B. (2020). Mechanical and durability performance of recycled aggregate concrete incorporating low calcium bentonite. *Construction and Building Materials, 237*, 117760. https://doi.org/10.1016/j.conbuildmat.2019.117760

Material resources management division. (2019). *100 million of tonnes construction aggregate for EEC construction project (5 years)*. https://www.bangkokbiznews.com/news/detail/844687

Memon, S. A., Arsalan, R., Khan, S., & Lo, T. Y. (2012). Utilization of Pakistani bentonite as partial replacement of cement in concrete. *Construction and Building Materials, 30*, 237-242. https://doi.org/10.1016/j.conbuildmat.2011.11.021

Mesboua, N., Benyounes, K., & Benmounah, A. (2018). Study of the impact of bentonite on the physico-mechanical and flow properties of cement grout. *Cogent Engineering, 5*(1). https://doi.org/10.1080/23311916.2018.1446252

Min, H. G., & Song, Z. G. (2018). Investigation on the sulfuric acid corrosion mechanism for concrete in soaking environment. *Advances in Materials Science and Engineering*. https://doi.org/10.1155/2018/3258123

Rehman, S. U., Kiani, U. A., Yaqub, M., & Ali, T. (2020). Controlling natural resources depletion through Montmorillonite replacement for cement-low cost construction. *Construction and Building Materials, 232*, 9. https//doi.org/10.1016/j.conbuildmat.2019.117188

Rehman, S. U., Yaqub, M., Noman, M., Ali, B., Khan, M. N. A., Fahad, M.,& Gul, A. (2019). The influence of thermo-mechanical activation of bentonite on the mechanical and durability performance of concrete. *Applied Sciences-Basel, 9*(24). https://doi.org/10.3390/app92 45549

Sandhu, R. K., & Siddique, R. (2017). Influence of rice husk ash (RHA) on the properties of self-compacting concrete: A review. *Construction and Building Materials, 153*, 751-764. https://doi.org/10.1016/j.conbuildmat.2017.07.165

Shakir, A. A., Ibrahim, M. H. W., Othman, N. H., & Shahidan, S. (2019). The Effect of palm oil clinker and oil palm shell on the compressive strength of concrete. *Iranian Journal of Science and Technology-Transactions of Civil Engineering, 43*, 1-14. https://doi.org/ 10.1007/s40996-018-0176-2

Shen, W. G., Zhang, W. S., Wang, J., Han, C. Z., Zhang, B. L., Li, J. W., & Xu, G. L. (2019). The microstructure formation of C-S-H in the HPC paste from nano-scale feature. *Journal of Sustainable Cement-Based Materials*, *8*(4), 199-213. https://doi.org/10.1080/21650373. 2018.1564397

Siddique, R., Singh, M., & Jain, M. (2020). Recycling copper slag in steel fibre concrete for sustainable construction. *Journal of Cleaner Production, 271*, 10. https//doi.org/10.1016/ j.jclepro.2020.122559

Umasabor, R. I., & Okovido, & J. O. (2018). Fire resistance evaluation of rice husk ash concrete. *Heliyon, 4*(12), e01035. https://doi.org/10.1016/j.heliyon.2018.e01035

Wiwattananukul, J., Sontamino, P., Masniyom, M., Rachpech, V., & Pantaweesak, P. (2019). *The Influence of the Population on the Use of Construction Aggregate in Songkhla Lake Basin* [Paper presentation]. In the 13th International Conference on Mining, Materials and Petroleum Engineering (CMMP2019), Krabi, Thailand.

Yu, Q., Sawayama, K., Sugita, S., Shoya, M., & Isojima, Y. (1999). The reaction between rice husk ash and $Ca(OH)_2$ solution and the nature of its product. *Cement and Concrete Research*, *29*(1), 37-43. https://doi.org/10.1016/S0008-8846(98)00172-0

Zahedi, M., Ramezanianpour, A. A., & Ramezanianpour, A. M. (2015). Evaluation of the mechanical properties and durability of cement mortars containing nanosilica and rice husk ash under chloride ion penetration. *Construction and Building Materials, 78*, 354-361. https://doi.org/10.1016/j.conbuildmat.2015.01.045

Vol. 20 No. 1: 39-55 [2021]
doi: 10.14416/j.appsci.2021.01.004

Zareei, S. A., Ameri, F., Dorostkar, F., & Ahmadi, M. (2017). Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties. *Case Studies in Construction Materials, 7*, 73-81. https://doi.org/10.1016/j.cscm.2017.05.001