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UTILIZATION OF CRUMB RUBBER AS AGGREGATE IN HIGH CALCIUM FLY ASH GEOPOLYMER MORTARS

Yuwadee Zaetang[1], Ampol Wongsa[2], Prinya Chindaprasirt[2,3] and *Vanchai Sata[2]

[1]Department of Civil and Environmental Engineering, Kasetsart University, Chalermphrakiat Sakon Nakhon Province Campus, Thailand; [2]Sustainable Infrastructure Research and Development Center, Department of Civil Engineering, Faculty of Engineering, Khon Kaen University, Thailand; [3]Academy of Science, The Royal Society of Thailand, Thailand

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ABSTRACT: This research was carried out to find out the possibility of utilizing tire crumb rubber waste as fine aggregate in fly ash-based geopolymer mortars (GPMs). The effect of replacement of river sand with crumb rubber at the levels of 0, 25, 50, 75, and 100% by volume on the geopolymer mortar properties including workability, dry density, compressive strength, flexural strength, thermal conductivity, ultrasonic pulse velocity (UPV), water absorption, and porosity were studied. The results were compared to those of the Portland cement-based mortars (PCMs). The test results demonstrated that the higher crumb rubber content resulted in the less dense matrix of mortar. However, GPMs with crumb rubber resulted in a significant improvement in flexural strength. The average ratio of flexural to compressive strengths of GPMs was 25% compared to 15% of PCMs. Also, the lower dry density and thermal conductivity of GPMs indicated better insulating properties than those of PCMs.

Keywords: Crumb rubber, Geopolymer, Mortar, NaOH, Sodium silicate solution

1. INTRODUCTION

The waste tire is one of the problematic sources of waste due to the huge discard quantity each year coupled with the containing of toxic elements and non-biodegradable materials. Landfilling of waste tires has been prohibited in some countries because it does not take up valuable landfill space as it is bulky and contribute to the rapid reduction of available areas for waste disposal. The stockpiles of waste tires also enlarge the risk of combustion, polluting the environment and provide breeding grounds for rodents and mosquitoes [1-3].

Tire recycling by the mechanical grinding process is breaking tires into small pieces and removing steel and fiber. Crumb rubber with a high irregular particle in the range of 0.42–4.75 mm can be obtained through this process. It has many applications including as an additive in rubberized asphalt, and as the main material to produce playground mulch and agricultural mulch. Also, many researchers indicated that crumb rubber could be used as construction aggregates in cement-based materials [4-7].

The flexural and compressive strength of mortar and concrete incorporating crumb rubber tend to decrease with an increase in the level of content [5, 6, 8]. Sofi [1] summarized the three reasons for the reduction. Firstly, a soft matrix of cement-based paste mixed with waste tire rubber led to the rapid development of cracks between rubber particles and paste. Secondly, low specific gravity of waste tire rubber compared to a natural aggregate increases the tendency for the floating of rubber particles to the top during vibration and leading to segregation. Finally, a lower bonding between cement-based paste and waste tire rubber particles compared to that between cement-based paste and natural aggregate led to the formation of cracks. However, the bond strength between the cement pastes and crumb rubber particles could be enhanced with the crumb rubber particle surface treatment with sodium hydroxide solution before incorporating in concrete. Segre et al. [9] used potentiometric titrations and infrared analysis to demonstrate that zinc stearate was removed from the recycled tire rubber surface after the sodium hydroxide treatment. This removal causes improved adhesion between the treated rubber and the cement-based matrix. Youssf et al. [10, 11] showed that pre-treatment by soaking crumb rubber particles for 0.5 hours in 10% sodium hydroxide solution recovered the compressive strength loss of crumb rubber concrete and the tensile strength was also increased. Also, the use of crumb rubber as a partially/fully replacement of aggregate for concrete exhibited an improvement of insulation properties such as thermal conductivity and acoustic impedance [4].

Geopolymer is an alternative cementitious material used as a binder or pastes to fabricate mortar and concrete instead of Portland cement-based material leading to the reduction of carbon footprint through a reduction in ordinary Portland cement consumption. Fly ash geopolymer-based composite is normally made with fly ash activated by alkaline solutions. Alkaline activators are used to dissolve the alumina and silica oxides in raw material and form geopolymer composite. The sodium hydroxide solution is a good alkaline activator for the production of geopolymer concrete [12-14]. The utilization of sodium hydroxide solution as an activator in crumb rubber geopolymer could also have the benefit of the surface treatment of rubber particles.

In this research, the influences of replacement level of river sand with crumb rubber on the properties of high calcium fly ash geopolymer mortars (GPMs) were investigated. The workability of fresh mortar, physical and mechanical of hardening mortars were investigated. The test results were also compared with Portland cement-based mortars (PCMs). This study should lay good groundwork for the future utilization of rubber waste in the geopolymer-based concrete product and thus lead to increased utilization of fly ash geopolymer composites.

2. MATERIALS

River sand and crumb rubber were used as aggregate. Lignite coal fly ash, sodium silicate solution, and 10 molar sodium hydroxide solution were used to prepare geopolymer-based binder, and Portland cement and tab water were the material used as a cement-based binder. The physical characteristics of all materials are shown in Table 1.

Table 1 Physical characteristics of aggregates and cementitious materials

Materials	Aggregates		Cementitious materials	
	Crumb rubber	River sand	Fly ash	Portland cement
Bulk density (kg/m^3)	487	1670	-	-
Fineness modulus	3.00	3.30	-	-
Water absorption (%)	3.27	0.35	-	-
Specific gravity (SSD)	1.16	2.63	2.17	3.15
Blaine fineness (cm^2/g)	-	-	2250	3120
Median particle size (micrometre)	-	-	32.6	14.1
Retained on a sieve No. 325 (%)	-	-	44	5

The crumb rubber was prepared by mechanized crushing of waste tires followed by sieving. The specific gravity was 1.16 similar to the other reported values of crushed waste tires [2, 15]. The SEM-photomicrographs of both aggregates showed that the surface texture of the crumb rubber particle was porous with the rough surface while river sand particle was dense and homogeneous as shown in Fig.1. Fig. 2 illustrates the particle size distribution of both river sand and crumb rubber with lower and upper limits as per ASTM C33.

Lignite coal fly ash was from Mae Moh electric power plant in northern Thailand. The chemical composition as analyzed by X-ray fluorescence (XRF) and X-ray diffraction (XRD) pattern of the lignite coal fly ash and Portland cement are shown in Table 2 and Fig.3. The fly ash could thus be categorized as Class C pozzolanic material and high-calcium fly ash based on ASTM C618.

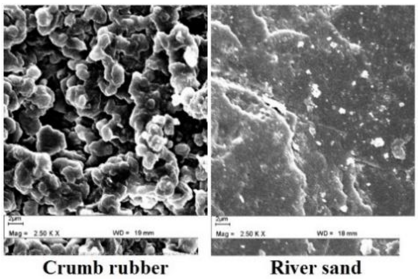

Fig. 1 Microstructure of aggregates

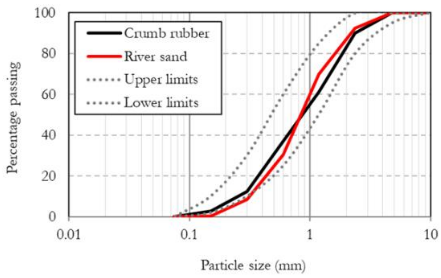

Fig. 2 Distribution of aggregate sizes with the lower and upper limits as per ASTM C33

Table 2 Chemical composition of cementitious materials

Oxides	Fly ash	Portland cement
CaO	14.5	61.1
SiO_2	39.4	18.1
Al_2O_3	20.8	4.2
Fe_2O_3	11.5	3.0
K_2O	2.4	0.6
MgO	2.2	1.1
Na_2O	1.4	0.2
P_2O_5	0.2	0.1
TiO_2	0.5	0.2
SO_3	4.2	3.9
Loss on Ignition (LOI)	1.5	5.9

The XRD pattern showed that fly ash contained some crystals of anhydrite (A, $Ca(SO_4)$), magnesioferrite (M, $MgFe_2O_4$), quartz (Q, SiO_2), and lime (O, CaO). Whereas ordinary Portland cement contained calcium silicate compounds (CS, Ca_3SiO_5, Ca_2SiO_4). The 10 molar sodium hydroxide solution (NaOH) was produced by dissolving 400 g of 98% purity sodium hydroxide pellets with distilled water while sodium silicate solution containing Na_2O of 12.53%, SiO_2 of 30.24%, and H_2O of 57.23% by weight was used without any modification.

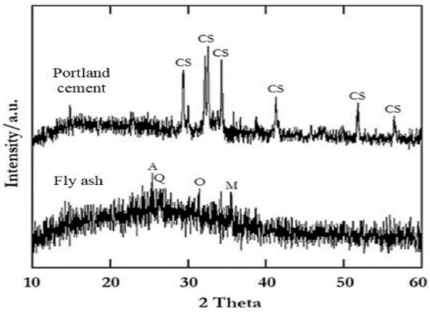

Fig. 3 XRD pattern

3. EXPERIMENTAL DETAILS

3.1 Mortar Mixtures

This study, five geopolymer-based and five Portland cement-based mortar mixtures were prepared to evaluate the influence of the replacement of river sand with crumb rubber on the properties of GPMs and PCMs. All mortar mixtures are presented in Table 3. The river sand to cementitious material (fly ash or Portland cement) ratio of 2.75 was used for geopolymer mortar (G0) and cement mortar (C0) without crumb rubber. The crumb rubber was also used to replace river sand at 0, 25, 50, 75, and 100% by volume. For GPMs, the alkaline solution to fly ash ratio of 0.75, the sodium silicate solution to the sodium hydroxide solution ratio of 1.0, and the sodium hydroxide solution concentration of 10 molars were used. For PCMs, the water to cement ratio of 0.48 was used to control the flow of PCM without crumb rubber (C0) at 110±5% as per ASTM C109 and ASTM C1437. The names of the mortar mixture were given by the type of cementitious materials and replacement volumes of crumb rubber. For example, G100 means the GPM with river sand replaced by crumb rubber at 100% by volume and C100 means the PCM with river sand replaced by crumb rubber at 100% by volume.

3.2 Specimen Preparation

The GPM mixtures were mixed in a pan mixer. Fly ash and sodium hydroxide solution were mixed for 5 minutes. Aggregates at a saturated surface dry condition were then added to the mixture and mixed for 5 minutes. Finally, the sodium silicate solution was added and mixed for another 5 minutes. After mixing, the fresh geopolymer mortar mixtures were cast into acrylic molds. The specimens were covered with cling film to prevent the moisture evaporation and left for 1 hour at 25 °C before heat curing. The samples were then applied with heat curing at 60 °C for 48 hours. After heat curing, specimens were stored in the controlled room at 25 °C and 50% R.H. until the testing age.

For PCM mixtures, ordinary Portland cement and water were also mixed in a pan mixer. River sand and/or crumb rubber was then added to the cement-based paste and mixed. After mixing, the fresh Portland cement mortar mixtures were placed into acrylic molds. The specimens were wrapped with cling film to avoid the moisture loss and were then demolded at the age of one day and stored in water till the testing age.

Table 3 Mix proportions of GPMs and PCMs

Mix	Aggregate		Geopolymer paste			Cement paste	
	River sand (g)	Crumb rubber (g)	Fly ash (g)	Sodium silicate (g)	NaOH (g)	Portland cement (g)	Water (g)
G0	2750	0	1000	375	375	-	-
G25	2062	240	1000	375	375	-	-
G50	1375	480	1000	375	375	-	-
G75	688	720	1000	375	375	-	-
G100	0	960	1000	375	375	-	-
C0	2750	0	-	-	-	1000	484
C25	2062	240	-	-	-	1000	484
C50	1375	480	-	-	-	1000	484
C75	688	720	-	-	-	1000	484
C100	0	960	-	-	-	1000	484

3.3 Testing of Specimens

For each mixture, the flow value of fresh mortar mixtures was measured as per ASTM C1437. The 5 cm cube specimens and the prisms with the dimensions of 4×4×16 cm were fabricated for the compressive strength test and the flexural strength test based on ASTM C109 and ASTM C78, respectively. The reported results were the average values of the three specimens. The dry density, ultrasonic pulse velocity (UPV, ASTM C597), and thermal conductivity were measured using 10 cm cube samples, while 5 cm cube samples were used to determine water absorption and porosity. The dry density, water absorption, and porosity were tested based on ASTM C642. The thermal conductivity value was monitored using a portable measuring instrument with a surface probe (ISOMET2114). The determination ranges of the instrument were 0.04–6.0 W/m.K.

4. RESULTS AND DISCUSSION

4.1 Flow Value

As shown in Fig. 4, the flow values of GPMs and PCMs ranged between 30-148% with suitable fluidity of fresh mortar ranging from plastic mortar to soft mortar without segregation. The GPMs provided greater flow values than the PCMs in the same replacement level of crumb rubber as a result of more liquid content as indicated in the alkaline solution to fly ash ratio of 0.75 compared to the water to Portland cement ratio of 0.48. However, the trends of the incorporation of crumb rubber in geopolymer and in Portland cement mortar mixtures were the same.

The results clearly showed that the increase in replacement level of crumb rubber decreased the flow values of fresh mortars for both systems. This was due to the higher surface area of crumb rubber that required more liquid for wetting the surface when compared to those with river sand as shown in Fig. 1. Consequently, it can be concluded that the replacement of river sand with crumb rubber in geopolymer or Portland cement mortars reduced the workability. Similar results were reported by previous studies [2, 16].

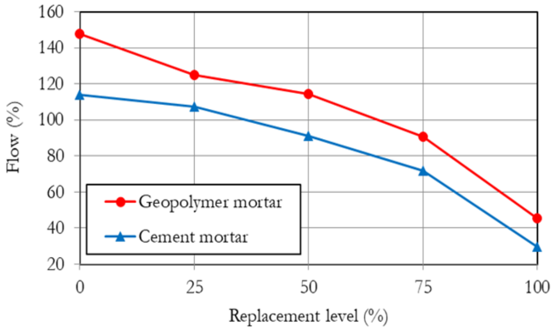

Fig. 4 Flow values

4.2 Compressive and Flexural Strengths

The 7, 28 and 60 days compressive strength of GPMs and PCMs containing crumb rubber are given in Table 4. The compressive strength increased with the curing age and the rate of gain of strength was high at an early age. Furthermore, the mixes of GPMs gained strength more rapidly than those of PCMs. Expressed as a percentage of the 28-days compressive strength to the strength at 7 days of GPMs and PCMs were approximately 92% and 84%, respectively. This was because 60 °C curing for 48 hours significantly increased the early age strength of geopolymer system [17, 18].

The influence of crumb rubber replacement level on compressive strength is illustrated in Fig. 5. The compressive strengths of GPMs and PCMs significantly decreased with the increase in crumb rubber content. It was also observed that the compressive strengths significantly decreased at 25% of the crumb rubber replacement level. For instance, the 28-days compressive strength of G25 and C25 decreased to 12.3 MPa (33% of G0) and 20.8 MPa (45% of C0), respectively. Beyond 50% of crumb rubber replacement, the trend of the compressive strengths of both GPMs and PCMs at different ages were also similar. Furthermore, when crumb rubber was used at 100% of the replacement level, the compressive strength of GPMs and PCMs were much reduced to similar values. The decrease in compressive strength was due to the lower modulus of elasticity of the crumb rubber particles compared to the typical mineral aggregates, as well as the weak bonding between paste and crumb rubber particles [15]. However, the compressive strength at 28 days of GPMs and PCMs containing crumb rubber in this study were in the range of 2.7-12.3 MPa and 3.3-20.8 MPa, respectively, which satisfied the compressive strength requirement values for moderate-strength lightweight concrete (2-14 MPa) based on ACI 213.

Table 4 Compressive and flexural strengths

Mix	Compressive strength (MPa)			Flexural strength (MPa)	Flexural to compressive strength ratio
	7 days	28 days	60 days	28 days	28 days
G0	28.9	37.4	44.0	4.4	0.12
G25	11.7	12.3	12.0	2.1	0.17
G50	6.1	6.5	7.2	1.7	0.26
G75	3.9	4.1	4.2	1.3	0.32
G100	2.7	2.7	3.5	1.0	0.37
C0	38.5	46.1	53.8	5.6	0.12
C25	17.0	20.8	21.8	3.3	0.16
C50	5.9	7.8	9.2	1.5	0.19
C75	3.9	4.3	5.2	0.8	0.19
C100	2.6	3.3	3.5	0.3	0.09

The increase in replacement level of crumb rubber decreased the flexural strength of GPMs and PCMs similar to the compressive strength as shown in Table 4. However, the reductions of flexural strength were different between GPMs and PCMs which could be visualized with the ratio of the 28-days flexural strength to compressive strength. This ratio of GPMs increased with the replacement levels of crumb rubber. The flexural to compressive strength ratios of G0, G25, G50, G75, and G100 were 12%, 17%, 25%, 34%, and 36%, respectively. However, this ratio of PCMs also increased with the replacement levels of the crump rubber up to 75%. Beyond this level of replacement, the flexural to compressive strength ratio of C100 dropped. The flexural to compressive strength ratios of C0, C25, C50, C75 and C100 were 12%, 16%, 19%, 19%, and 9%, respectively. The average ratio of flexural to compressive strengths of GPM mixtures was 25% which was higher than that of PCM mixtures (15%). It is worth to note that the using of crumb rubber as fine aggregate to replace river sand resulted in significant improvement in flexural strength for GPMs. This may be because of the high concentration of sodium hydroxide solution in geopolymer caused a surface treatment of crumb rubber. Some researches mentioned the improvement of surface adhesion between the rubber particles and cement paste by soaking particles in the solution of sodium hydroxide before being used in concrete work. Youssf et al. [10, 11]

reported the positive effects of using sodium hydroxide solution pre-treatment for rubber particles on the mechanical performance of concrete. The rubber particles were surface-treated with a sodium hydroxide solution before incorporating in concrete. It increased the tensile strength by 15% and increased the concrete compressive strength by 6% at 7 days and 15% at 28 days compared to non-treated. Segre et al. [9] also found that the sodium hydroxide solution can remove the zinc stearate layers on surface rubber, leaving carbon black to enhance the polarity of the surface, playing an important role for the adhesion of the treated rubber to the cementitious matrix.

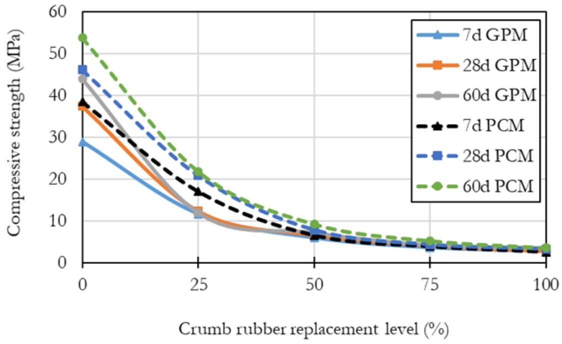

Fig. 5 Compressive strength

4.3 Dry Density, Thermal Conductivity and UPV

The test results of dry density, thermal conductivity, and UPV are summarized in Table 5. The densities of GPMs ranged from 1075-1950 kg/m^3 and were slightly less than those of PCMs (1299-2150 kg/m^3). At the same replacement level of crumb rubber, the PCMs exhibited a higher density than those of GPMs. This was due to the lower specific gravity of fly ash compared with Portland cement (Table 1). As expected, the density of GPMs and PCMs decreased with the replacement level of crumb rubber. This was because of the lower specific gravity and bulk density of crumb rubber compared with river sand. Besides, the density of GPMs and PCMs containing high-volume of crumb rubber at 75 and 100% were in the range of the density requirement values for lightweight moderate-strength concrete (1000-1400 kg/m^3) based on ACI 213. The density in the study was also related to the compressive strength test results of GPMs and PCMs as shown in Fig.6. The compressive strength increased with the increase in the dry density of mortar specimens. The empirical equation relating to compressive strength and dry density is obtained as:

$$\sigma = 0.0910e^{0.0030D};\ R^2 = 0.9705 \text{ for GPMs} \quad (1)$$
$$\sigma = 0.0443e^{0.0032D};\ R^2 = 0.9908 \text{ for PCMs} \quad (2)$$

Where σ is compressive strength (MPa), and D is dry density (kg/m^3).

Table 5 Dry density, thermal conductivity and UPV of GPMs and PCMs

Mix	Dry density (kg/m^3)	Thermal conductivity (W/m.k)	UPV (m/s)
G0	1950	1.065	1995
G25	1697	0.576	1288
G50	1480	0.410	1144
G75	1302	0.284	958
G100	1075	0.187	719
C0	2150	1.699	3347
C25	1853	1.084	2684
C50	1620	0.638	1699
C75	1438	0.401	1128
C100	1299	0.287	1048

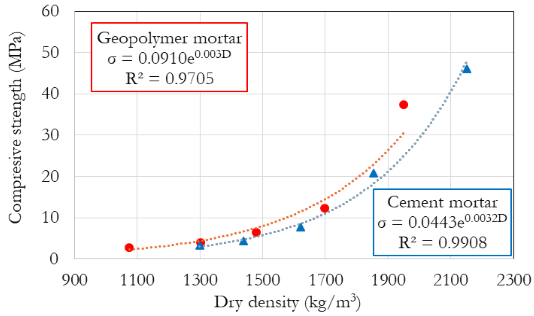

Fig. 6 Compressive strength and dry density

With regards to thermal conductivity, a previous study [19] reported that the thermal property depended on types of source materials and density of mortar and concrete. In this study, the thermal conductivity of GPMs and PCMs depended on the types of binders and the replacement level of crumb rubber. The thermal conductivity of GPMs (0.187-1.065 W/m.K) were less than those of PCMs (0.287-1.699 W/m.K) due to the lower specific gravity of solid binder (fly ash) and the higher liquid to solid binder ratio compared with those of Portland cement. The increase in replacement level of crumb rubber also decreased the thermal conductivity of both mortars in the study because of the lower specific gravity and bulk density as well as the higher porosity of crumb rubber compared with river sand as shown in Fig. 1. The air void or porosity of composites was the lowest thermal conductivity compared with the liquid and solid and this resulted in the reduction of thermal conductivity [20-21]. Moreover, the results indicated that the dry density and thermal conductivity are related shown in Fig. 7. The empirical equation relating to thermal conductivity and dry density is obtained as:

$$T = 0.0224e^{0.0020D};\ R^2 = 0.9955 \text{ for GPMs} \quad (3)$$
$$T = 0.0193e^{0.0021D};\ R^2 = 0.9885 \text{ for PCMs} \quad (4)$$

Where T is thermal conductivity (W/m.K), and D is dry density (kg/m^3)

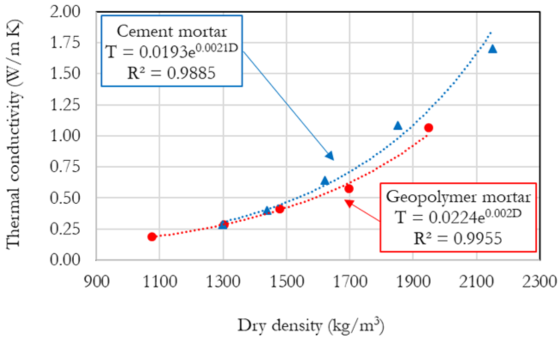

Fig. 7 Thermal conductivity and dry density

The UPV values or the time elapsed of the ultrasonic wave to pass through an object was correlated with its density. The UPV values of GPMs and PCMs were ranged 719-1995 and 1048-3347 m/s, respectively. The UPV values of GPMs were less than those of PCMs and also consistent with the previously published report [19]. The UPV values of geopolymer-based concrete were less than those of ordinary Portland cement-based concretes because the specific gravity of FA was less than Portland cement. Moreover, the increase of crumb rubber replacement level decreased the UPV values of GPMs and PCMs. Many researchers [21, 22] indicated that the UPV values of geopolymer-based composites depended on the density of mortar and concrete. The increase in crumb rubber content thus resulted in a decrease in density and UPV values as shown in Fig. 8. The UPV values increased with the increase of dry density which was similar to the thermal conductivity results. The UPV and the dry density can be expressed as:

$U = 222.01e^{0.0011D}$; $R^2 = 0.9733$ for GPMs (5)
$U = 147.28e^{0.0015D}$; $R^2 = 0.9625$ for PCMs (6)

Where U is UPV (m/s), and D is dry density (kg/m^3)

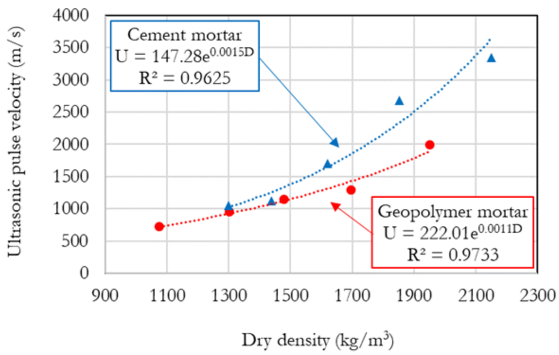

Fig. 8 UPV and dry density

Furthermore, the UPV values in the study were also related to the test results of compressive strength. Shankar and Joshi [23] and Ghosh et al. [24] explained the UPV test for assuring the concrete quality and explained that the UPV values of geopolymer-based and Portland cement-based concretes increased with the compressive strength as shown in Fig. 9. As can be seen, the UPV values increased with the increase of compressive strength and can be expressed as:

$\sigma = 0.6035e^{0.0021U}$; $R^2 = 0.9737$ for GPMs (7)
$\sigma = 1.1562e^{0.0011U}$; $R^2 = 0.9949$ for PCMs (8)

Where σ is compressive strength (MPa), and U is UPV (m/s).

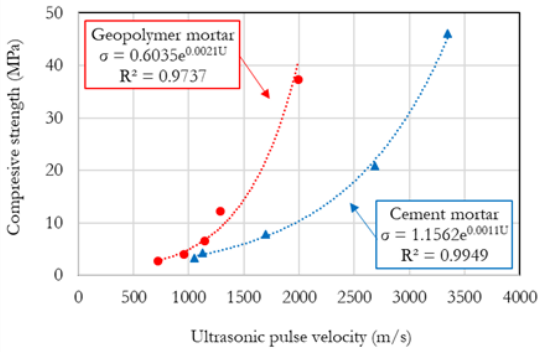

Fig. 9 Compressive strength and UPV

4.4. Water Absorption and Porosity

The water absorption and porosity of GPMs and PCMs are summarized in Table 6. The porosity values of GPMs (18.3-28.8) were slightly higher than those of PCMs (18.2-28.0%). This may be due to the higher binder to the liquid ratio of geopolymer-based paste compared with that of Portland cement-based paste. To elucidate, the alkaline solution to fly ash ratio of 0.70 was used to prepare GPMs while the water to cement ratio of 0.48 was used to make PCMs. The previous study [18] indicated that the porosity value of geopolymer-based paste with liquid alkaline to fly ash ratio of 0.65 was 25.1% while the porosity value of Portland cement-based paste with water to cement ratio of 0.48 was 17.7%. Moreover, Kim et al. [25] also reported that the increase in water to cement ratios (additional water amount) from 0.45 to 0.60 increased the porosity of cement-based mortars up to 150%. Abdullah et al. [26] claimed that the volume of voids and porosity depended on the solid to the liquid ratio which directly influences the physical and mechanical properties of the geopolymer-based composite. The porosity of GPMs and PCMs increased with the replacement level of crumb rubber. This was because of the higher porosity of crumb rubber particles compared with river sand particles. The increase in porosity thus resulted in the reduction of density, thermal conductivity, UPV, and compressive strength.

With regards to the water absorption test, the water absorption values of GPMs were higher than those of PCMs. Besides, the test results also showed that the water absorption of GPMs and PCMs increased with the replacement level of crumb rubber which were consistent with the results of porosity. Moreover, the water absorption of GPMs and PCMs increased with the immersion age as shown in Fig. 10. The rate of increase of the water absorption significantly depended on the crumb rubber contents. The average rate of the increase in water absorption of high crumb rubber volume mortars was higher than those of low and without crumb rubber mortars. On average, the 42 days water absorption of samples with replacement level of crumb rubber at 0, 25, 50, 75, and 100% were 3, 8, 21, 23, and 26% for GPMs and 6, 7, 13, 23, and 32% for PCMs, respectively.

Table 6 Porosity and water absorption of GPMs and PCMs

Mix	Porosity (%)	Water absorption (%)					
		7 days	14 days	21 days	28 days	35 days	42 days
G0	18.3	8.4	8.3	8.4	8.6	8.8	8.7
G25	18.9	9.9	10.0	10.1	10.5	10.8	10.7
G50	22.9	11.8	12.5	12.9	13.8	14.6	14.9
G75	26.0	14.6	15.8	16.5	17.6	18.6	18.9
G100	28.8	18.4	20.2	21.2	22.8	24.3	24.9
C0	18.2	8.3	8.4	8.5	8.6	8.7	8.8
C25	18.5	9.3	9.5	9.7	9.8	9.9	10.0
C50	20.8	11.0	11.6	12.0	12.3	12.5	12.6
C75	24.2	13.1	14.9	15.9	16.5	16.7	16.9
C100	28.0	15.8	19.7	21.6	22.5	22.9	23.3

5. CONCLUSION

The results of this investigation could be summarized as follows:

1) The compressive strengths of GPMs and PCMs significantly decreased with the increasing crumb rubber replacement level. However, the GPMs with strength range of 2.7-12.3 MPa can be used as the moderate-strength concrete for lightweight applications.

2) The using of crumb rubber as a fine aggregate to replace river sand increased the ratio of flexural to compressive strengths of GPMs which resulted in significant improvement in flexural strength for geopolymer-based mortars. While those of PCMs were also improved but to a lesser extent.

3) The increase in replacement content of crumb rubber of GPMs and PCMs decreased the flow values of fresh mortars and decreased thermal conductivity, dry density, and UPV, while increased the porosity and water absorption.

4) The densities of GPMs and PCMs containing crumb rubber at high-volume of 75% and 100% were within the requirement of a lightweight moderate-strength concrete based on ACI 213. Moreover, the lower dry density and thermal conductivity of GPMs comparing to PCMs indicated a better insulating property.

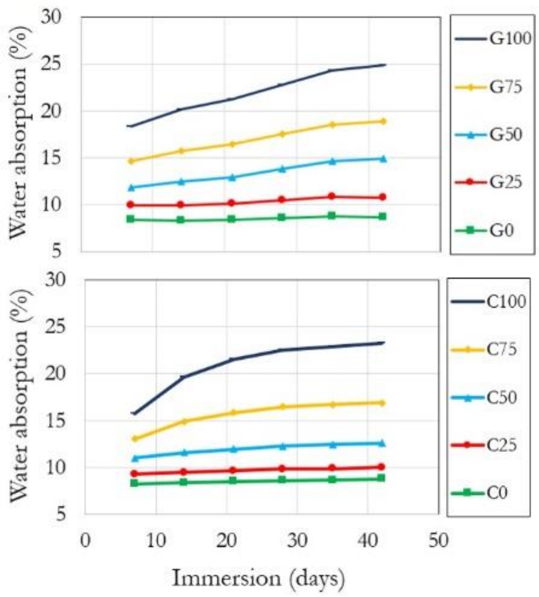

Fig. 10 Water absorption of GPMs and PCMs

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