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Utilization of ceramic waste as fine aggregate within Portland cement and fly ash concretes

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ABSTRACT

The aim of this research work was to investigate the feasibility of using ceramic waste and fly ash to produce mortar and concrete. Ceramic waste fragments obtained from local industry were crushed and sieved to produce fine aggregates. The measured concrete properties demonstrate that while workability was reduced with increasing ceramic waste content for Portland cement concrete and fly ash concrete, the workability of the fly ash concrete with 100% ceramic waste as fine aggregate remained sufficient, in contrast to the Portland cement control concrete with 100% ceramic waste where close to zero slump was measured. The compressive strength of ceramic waste concrete was found to increase with ceramic waste content and was optimum at 50% for the control concrete, dropping when the ceramic waste content was increased beyond 50%. This was a direct consequence of having a less workable concrete. However, the compressive strength in the fly ash concrete increased with increasing ceramic waste content up to 100%. The benefits of using ceramic waste as fine aggregate in concrete containing fly ash were therefore verified.

1. Introduction

Industrial wastes have continued to increase due to the continued demands of resource use by humans. For these wastes to be incorporated into concrete, they can either be used as part of the cement mixture or as aggregate in concrete in order to maintain the sustainability of this construction material. Some wastes or by-products have been successfully utilized, such as in the case of fly ash for use as a constituent in cement to produce Portland-fly ash cement (with the optimum percentage found to be in the region of 30%) [1–5]. Many waste or by-products in sizes larger than cement particles may be used as aggregates in mortar or concrete. These materials vary from sintered fly ash, to crushed brick, to polystyrene aggregate [6–13]. Structural lightweight concretes have been recently produced from recycled polystyrene [10], recycled crushed clay brick [11], waste polyethylene terephthalate bottles [12], or recycled glass cullet [13], as aggregates. Tang et al. [10] report that the compressive strength of concrete using polystyrene as aggregate decreased considerably with an increase of polystyrene content in the mix. Kou and Poon [13] studied the feasibility of recycled glass cullet in concrete as aggregate replacement. The results show that the slump flow, blocking ratio, and air content of the recycled glass concrete mixes increased with increasing recycled glass content. However, the compressive strength, tensile splitting strength, and static modulus of elasticity of the recycled glass concrete mixes decreased with an increase in the recycled glass aggregate content.

Earthenware from ceramic industries (producing vases, teapots, small earthen pots, or other porcelains) is used extensively for pottery tableware and decorative objects. This earthenware is commonly produced from clay or china clay, which is fired to temperatures in a range of 1000–1150 °C. Some of these products, which were cracked during the sintering process, would then go to waste. This waste accounts for as much as 30% of the overall production of the local ceramic industry [14]. Coincidentally, ceramic waste also accounts for 30% of all demolition wastes [15]. Although the ceramic industries have attempted to find appropriate solutions for waste disposal, ceramic waste cannot presently be reused in the production of new material. Therefore, due to these manufacturing criteria, the amount of ceramic waste will continue to increase. However, ceramic waste has several positive features: it is hard, durable, and highly resistant to chemicals. In this regard, the properties of ceramic wastes are such that they would be potentially suitable for reuse in a composition of mortar or concrete.

It has been reported that ceramics in the form of hollow bricks used in non-structural concrete has lower compressive strength than that of control concrete without the use of hollow bricks [16]. Furthermore, theses hollow bricks were found to have a high water absorption [16–18]. When electrical insulator ceramics, another ceramic type, are used as coarse aggregate, they are found to possess similar strength to that of conventional concrete [19].

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However, earthenware ceramics are smaller in size when crushed compared to the electrical insulator ceramics and do not produce water absorption problems like hollow bricks; thus, they have the potential for use as fine aggregate. At present, utilization of this conventional ceramic waste in concrete is still not well established – primarily due to a lack of public information, especially in comparison with other types of cement such as fly ash cement.

This work investigates the effects of earthenware ceramic waste used as fine aggregates on properties of Portland cement and fly ash concretes. In addition, the effect of this ceramic waste on the properties of Portland cement and fly ash mortars were also investigated and these results are also given and discussed.

2. Experimental program

2.1. Materials

Ordinary Portland cement type I, fly ash, crushed limestone, natural sand, ceramic waste aggregate, and water of drinking quality were used in this study.

Lignite fly ash (FA), a by-product of the Mae Moh power plant in the north of Thailand, was used as a Portland cement supplementary material at 30% by weight. The chemical composition of ordinary Portland cement type I (PC) and fly ash are given in Table 1. Scanning electron microscope (SEM) observations show angular shape of PC particles (Fig. 1a) that the particle shapes of FA are spherical with a smooth surface (Fig. 1b).

Ceramic waste aggregate (CWA) used in this study was obtained from ceramic industries in Lampang province, Thailand. Ceramic waste pieces are generally too large in size (Fig. 2a), so they were broken by a hammer into smaller pieces (⩽10 mm). These small pieces were crushed using a jaw crusher until the percentage passing a sieve mesh No. 4 (opening 4.75 μm) was 100%. The particle size distribution of CWA used in the investigation was kept the same as that of sand by using sieves of mesh Nos. 4, 8, 16, 30, 50 and 100 in order to provide a direct comparison of their effects on compressive strength; the photograph of CWA is shown in Fig. 2b. The results of the sieve analysis for sand and CWA used as fine aggregate can be seen in Fig. 3. The particle size distributions of both sand and CWA were kept the same in order to allow direct comparison of the results. Maximum particle size, water absorption, and specific gravity of CWA were 4 mm, 1.25% by mass, and 2.31, respectively. Particle shapes and surface texture of CWA, which were observed using an optical microscope (OM) and SEM, are shown in Fig. 2d and 2f, respectively. It can be seen that CWA is angular in shape, and its surface texture was found to be rougher than that of sand. This was due to fractures caused by the crushing process.

Table 1
The chemical composition of ordinary Portland cement type I and fly ash.

Compound	Composition (%)	
	Ordinary Portland cement type I	Fly ash
Silicon dioxide (SiO_2)	24.41	40.49
Aluminum oxide (Al_2O_3)	5.65	20.04
Ferric oxide (Fe_2O_3)	3.62	13.54
Calcium oxide (CaO)	59.15	11.27
Magnesium oxide (MgO)	1.18	6.26
Sodium oxide (Na_2O)	0.47	4.21
Potassium oxide (K_2O)	0.54	1.55
Sulfur trioxide (SO_3)	2.64	1.78
Manganese oxide (MnO)	0.43	0.28
Phosphorus pentoxide (P_2O_5)	0.31	0.26
Titanium dioxide (Ti_2O)	0.29	0.21
Loss on ignition (LOI)	1.31	0.11

Natural sand with a maximum particle size of 4 mm was used in all mortar mixtures. Water absorption and specific gravity of the sand are ≈1.0% by mass and 2.58 respectively. Particle shapes and surface texture of sand, observed using OM and SEM, are shown in Fig. 2e andg, respectively. As can be seen in Fig. 2e, the particle shape of sand is slightly angular, with a smoother surface texture (Fig. 2g) than that of CWA (Fig. 2f).

Crushed limestone was used as coarse aggregate with a maximum size of 19 mm according to ASTM C33 [20]. The particle size distribution of crushed limestone is shown in Fig. 3.

2.2. Mixture proportions

2.2.1. Mortar

In order to investigate the potential use of CWA and FA as a substitute for sand and ordinary Portland cement respectively, two sets of mixes were prepared. For the first set – Portland cement mortar – CWA was used as sand replacement at 0%, 10%, 20%, 30%, 40%, 50% and 100% by weight. In the second set of mixes – FA mortar – FA was used as ordinary Portland cement replacement at 30% by weight, and sand was replaced with ceramic waste at 0%, 50% and 100% by weight. A constant water to binder ratio (w/cm) of 0.5 by mass was used throughout the investigation. Mixture proportions of mortars with and without FA are presented in Table 2.

2.2.2. Concrete

Mixture proportions of both Portland cement concrete and 30% FA concrete mixes are shown in Table 2. CWA was used as a natural sand replacement at 0%, 50% and 100% by weight for both sets of concrete. The binder was mixed with water, and both fine and coarse aggregates, using a water to binder ratio of 0.56 by mass.

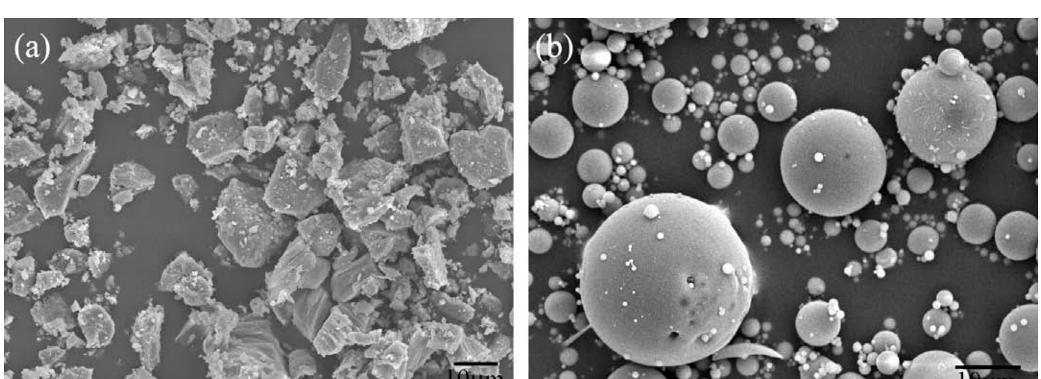

Fig. 1. SEM micrograph of (a) Portland cement and (b) fly ash.

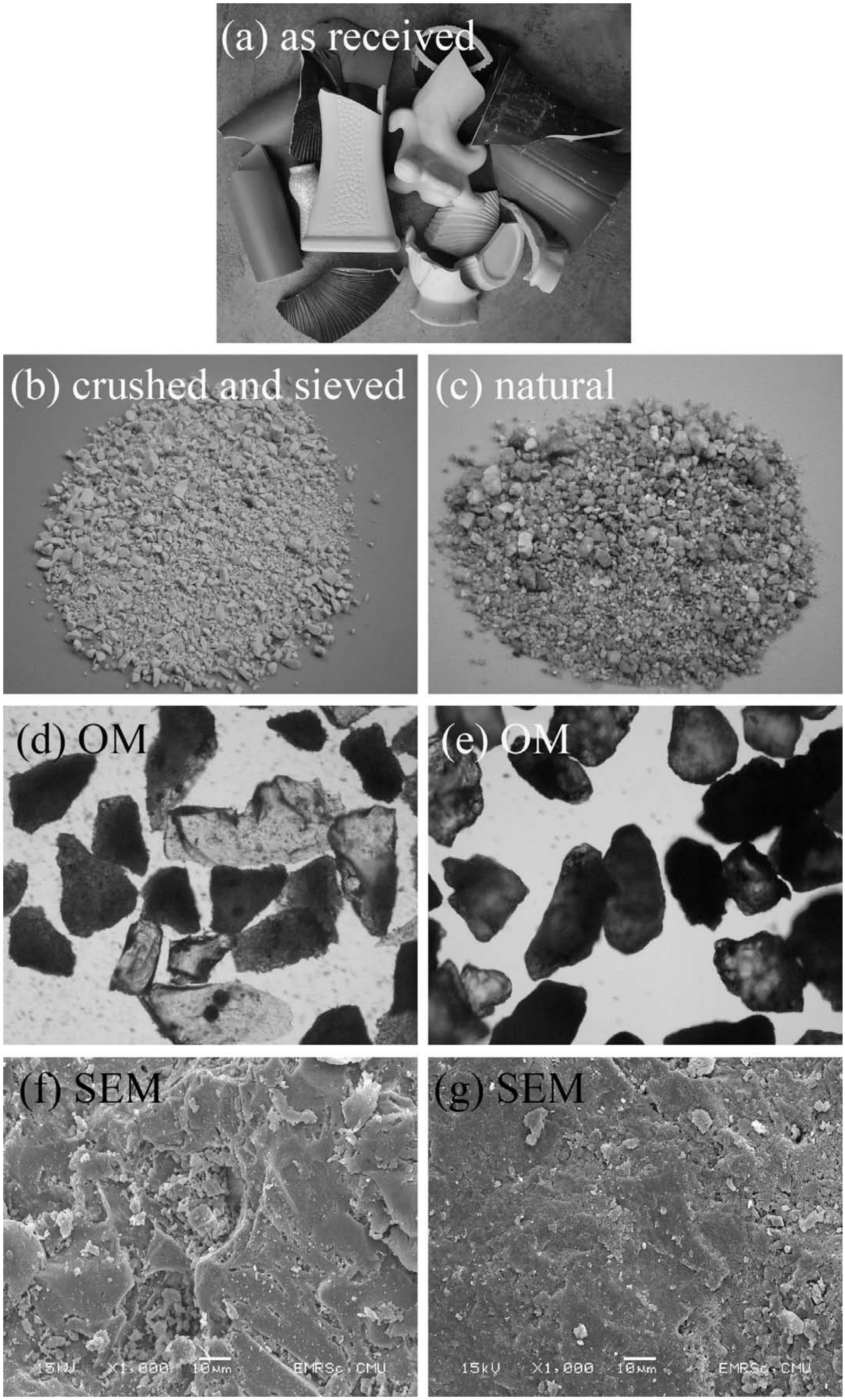

Fig. 2. Illustration of (a) as received CWA, (b) crushed CWA, (c) natural sand aggregate, (d) OM of CWA, (e) OM of natural sand, (f) SEM of CWA surface, and (g) SEM of natural sand surface.

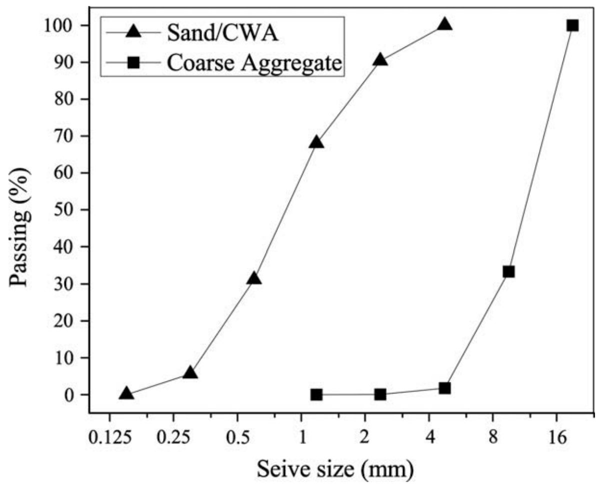

Fig. 3. Grain size distribution of fine and coarse aggregate.

2.3. X-ray diffraction (XRD)

The crystalline phases of natural sand and CWA were investigated using an XRD technique. Both fine aggregates were ground and sieved through a sieve mesh No. 100 (opening 150 μm). A powder sample weighing about 5 g was used to determine the crystalline phases in the XRD analysis, and measurements were made with a 2θ step interval of 5°–90°. XRD analysis (Fig. 4) shows that sand is comprised of mainly crystalline phase of silicon dioxide (JCPDS No. 88-2302), which gives the strong intensity peaks appearing at 2θ of 20.86°, 26.65°, 36.55°, 39.48°, 50.15° and 59.98°. The intensity peaks of CWA appeared at 2θ of 25.99°, 26.27°, 30.96°, 33.23°, 35.25°, 40.85°, 42.61°, 49.44°, 54.07°, 60.69°, 64.52° and 70.46° (Fig. 4). CWA consists of a minor glassy phase with strong crystalline phase. The strong intensity peaks of CWA in the XRD patterns are quite similar to that of mullite (JCPDS No. 83-1881) which is the crystal structure of an aluminosilicate after firing at approximately 1050–1100 °C.

2.4. Density of mortar and concrete

The wet bulk density of sand mortars and CWA mortars at the age of 28 days was investigated. The tested mortars were weighed in water, and this mass was recorded as *A*. After that, mortars were removed from water, surface-dried by removing the surface moisture with a towel, and weighed in air. This saturated surface-dry mass was designated as *B*. The masses of *A* and *B* were then used to determine wet bulk density, with calculations as follows, where p_w is the density of water [21]:

$$\text{Wet bulk density}(\text{g/cm}^3) = \frac{B}{B-A} \times \rho_w$$

The reported wet bulk density is the average of three samples.

2.5. Workability

2.5.1. Mortar

The workability of mortar in this investigation was determined according to ASTM C1437-01 [22]. Each mortar mix was filled in a mold placed at the center of a flow table, and the mix was then tamped. The mortar was then cut off to a plane surface finish at the top of the mold. Diameters of the mortar were measured along four lines, in mm.

2.5.2. Concrete

The workability of concrete in this study was investigated according to ASTM C143 [23]. A slump mold was placed on a flat surface and then filled with mixed concrete. The fresh concrete was stoked by using a tamping rod 25 times at three different layers. After the top layer had been tamped, the surface of the

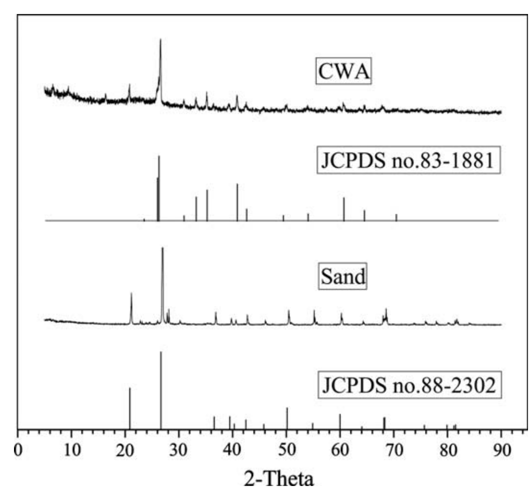

Fig. 4. X-ray diffraction patterns of sand and CWA.

Table 2
Mixture proportions of mortars and concretes.

Mix	Binder (% by weight)		Aggregate (% by weight)		Free W/B
	PC	FA	Sand	CWA	
M0CWA0FA (control)	100	0	100	0	0.5
M10CWA0FA	100	0	90	10	0.5
M20CWA0FA	100	0	80	20	0.5
M30CWA0FA	100	0	70	30	0.5
M40CWA0FA	100	0	60	40	0.5
M50CWA0FA	100	0	50	50	0.5
M100CWA0FA	100	0	0	100	0.5
M0CWA30FA	70	30	100	0	0.5
M50CWA30FA	70	30	50	50	0.5
M100CWA30FA	70	30	0	100	0.5
C0CWA0FA (control)	100	0	100	0	0.56
C50CWA0FA	100	0	50	50	0.56
C100CWA0FA	100	0	0	100	0.56
C0CWA30FA	70	30	100	0	0.56
C50CWA30FA	70	30	50	50	0.56
C100CWA30FA	70	30	0	100	0.56

concrete was struck off by means of a screening and rolling motion of the tamping rod. The mold was immediately removed from the concrete by raising it carefully in a vertical direction. The slump was immediately measured by determining the vertical difference between the top of the mold and the displaced original center of the top surface of the specimen.

2.6. Compressive strength

2.6.1. Mortar

Mortar constituents were mixed in a mechanical mixer. Afterward, the mixes were cast in 50 mm cube molds, and then compacted in two layers using a tamping rod. The fresh samples were smoothed and covered with plastic film to prevent water loss. After setting for 24 h, the specimens were removed from the molds and were cured in pH 12 water at 23 ± 1.7 °C. Compressive strength tests were carried out at 7, 14 and 28 days. The reported results are the averages of three samples.

2.6.2. Concrete

The compressive strength of concrete was tested according to ASTM C192 [24]. Concrete constituents were mixed in a mechanical mixer. Afterward, the mixes were cast in 100 mm cube molds, and then compacted in two layers using a tamping rod. The fresh samples were smoothed and covered with plastic film to prevent water loss. After setting for 24 h, the specimens were removed from the molds and were cured in pH 12 water at 23 ± 1.7 °C. Compressive strength tests were carried out at 7 and 28 days. The reported results are the averages of three samples.

2.7. Scanning electron microscopy (SEM)

Raw materials and fragments of specimens tested for compressive strength after compression were characterized for morphology and chemical characteristics at the Electron Microscopy Research and Service Center (EMRSC) of Chiang Mai University using low vacuum SEM with a JEOL JEM-5910LV microscope linked to an energy-dispersive X-ray spectrometry (EDS) unit. SEM samples were attached to double-sided carbon tape mounted on a brass stub. All samples were also coated with gold, using 10–20 mA DC current, before inserting the samples into the instrument. The elemental composition and morphology were determined for each sample.

3. Results and discussion

3.1. Effect of CWA substitution on density of mortars

3.1.1. Density of mortars without fly ash

The effect of CWA replacement as fine aggregates at 0%, 10%, 20%, 30%, 40%, 50% and 100% by weight on the density of Portland cement mortars at 28 days is given in Fig. 5. The results indicated that wet bulk densities of mortars with CWA were lower than that of control mortar, and were found to decrease with increasing CWA content. The density of the mortar with 100% CWA was 2.04 g/cm^3, which was a 6.85% decrease when compared to the control mix (M0CWA0FA). This was due to CWA having a lower specific gravity than that of natural aggregate. Moreover, it can be seen that the reduction in the density with respect to the amount of CWA appears to be linear with a correlation factor (R^2 value) close to 1 (0.988).

3.1.2. Densities of mortars with fly ash

The effect of CWA replacement as fine aggregates at 0%, 50% and 100% by weight on the density of fly ash mortars at 28 days is shown in Fig. 5. It can be seen that the density trend of fly ash mortars was similar to those of Portland cement mortars, decreasing with increasing CWA content. The densities of fly ash mortars with 50% and 100% CWA are about 8 g/cm^3 and 15 g/cm^3 lower, respectively, than the reference fly ash mortar (M0CWA30FA). Again, this reduction in the density can be seen to be linear with the correlation of 0.996.

3.2. Effect of CWA substitution on density of concretes

3.2.1. Densities of concretes without fly ash

The effect of CWA replacement as fine aggregates at 0%, 50% and 100% by weight on the density of Portland cement concretes is shown in Fig. 5. The results show that wet bulk density of con-

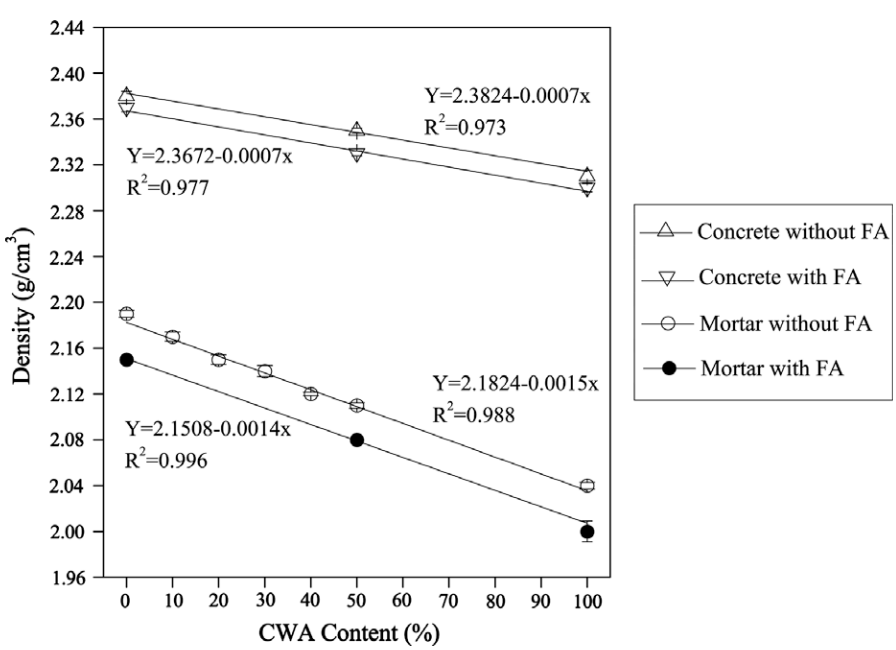

Fig. 5. The effect of CWA replacement as fine aggregates on density of mortars and concretes.

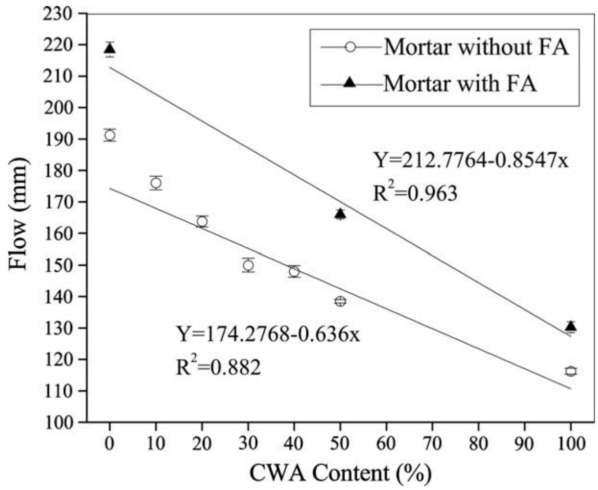

Fig. 6. The effect of CWA replacement as fine aggregates on workability of mortar with and without FA.

cretes with CWA was lower than that of control concrete, and was found to decrease with increasing CWA content. This would agree with the results of the mortars, as reported earlier. The density of the concrete with 100% CWA was 2.31 g/cm^3, which was 0.07 g/cm^3 lower than that of the control mix (2.38 g/cm^3). These results indicate that concretes containing CWA produce a lower density than that of conventional concrete (C0CWA0FA), due to lower specific gravity of CWA. In addition, the concrete density can be seen to reduce linearly with the correlation factor of 0.973.

3.2.2. Densities of concretes with fly ash

The effect of CWA replacement as fine aggregates at 0%, 50% and 100% by weight on density of FA concretes at 28 days is shown in Fig. 5. Again, the density trend of FA concretes was similar to those of Portland cement concrete. It can be seen that the densities of FA concretes with 50% and 100% CWA are about 0.04 and 0.07 g/cm^3 lower, respectively, than the reference FA concrete (C0CWA30FA). A linear relationship can once again be seen ($R^2 = 0.977$).

3.3. Effect of CWA substitution on workability of mortars

3.3.1. Workability of mortars without fly ash

The effect of CWA replacement as fine aggregates at 0%, 10%, 20%, 30%, 40%, 50% and 100% by weight on the workability of Portland cement mortars is presented in Fig. 6. Relative workability of Portland cement mortars is given in Fig. 7a. The workability of mortars was assessed based on the measured flow of fresh mortar. The results show that the flow of mortar significantly decreased with the increase of CWA content. The flow of the M100CWA0FA mortar using CWA at 100% by weight was approximately 116 mm, which was a 39.2% decrease when compared to the control mix (M0CWA0FA) (Fig. 7a). This was due to the angular shape of CWA, which caused a reduction in the workability of mortars and thus was more difficult to compact.

3.3.2. Workability of mortars with fly ash

The effect of fly ash replacement of Portland cement at 30% by weight on the workability of mortars with CWA is shown in Fig. 6. Relative workability of fly ash mortars is given in Fig. 7b. The results indicate that the trend of flow of FA mortars was similar to those of Portland cement mortars, but with FA mortars having a higher flow throughout. The flow of FA mortar using 100% CWA (M100CWA30FA) is about 31.9% lower than that of the control mix (Fig. 7b). However, this represents around a 12.0% gain compared to that of the 100% CWA mortar without FA (M100CWA0FA). The moderate increase of the flow of this mix is due to the spherical shape and smooth surface of fly ash, which enhanced the flow and workability of FA mortars [25].

3.4. Effect of CWA substitution on workability of concretes

3.4.1. Workability of concretes without fly ash

The effect of CWA replacement as fine aggregates at 0%, 50% and 100% by weight on the workability of concretes can be seen in Fig. 8a. Relative workability of Portland cement concrete is given in Fig. 8b. The workability of concretes was assessed based on the measured slump of fresh concrete. The results indicated that the slump of concretes was clearly reduced with increasing CWA content. Nonetheless, no detrimental effect in the slump value was found at CWA of 50% (110 mm), where the slump values were similar to the control Portland cement concrete. However, when using CWA at 100% to produce concrete, the slump values dropped to close to zero (5 mm); this can be regarded as a no-slump concrete, where the concrete was not workable. This finding can be explained by the rough, angular nature of CWA which reduces the workability of concrete mixes in the fresh state. A similar result was found by Ismail and AL-Hashmi [26], where the slump of concrete using waste plastic as sand replacement was found to be reduced due to the angular and non-uniform shapes of the waste plastic. In this study, one interesting observation was that the

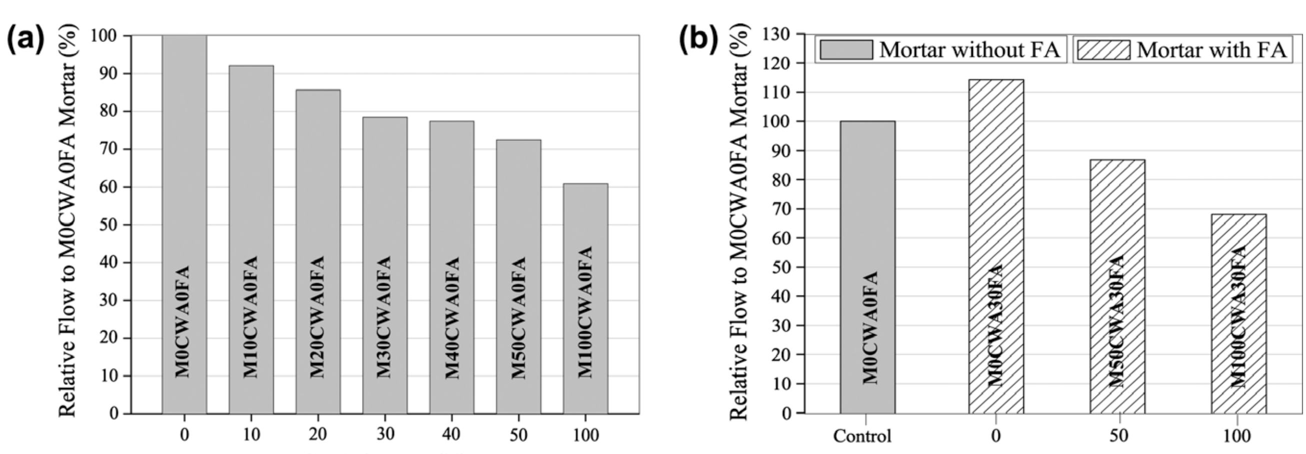

Fig. 7. Relative workability of (a) mortar without FA and (b) mortar with FA.

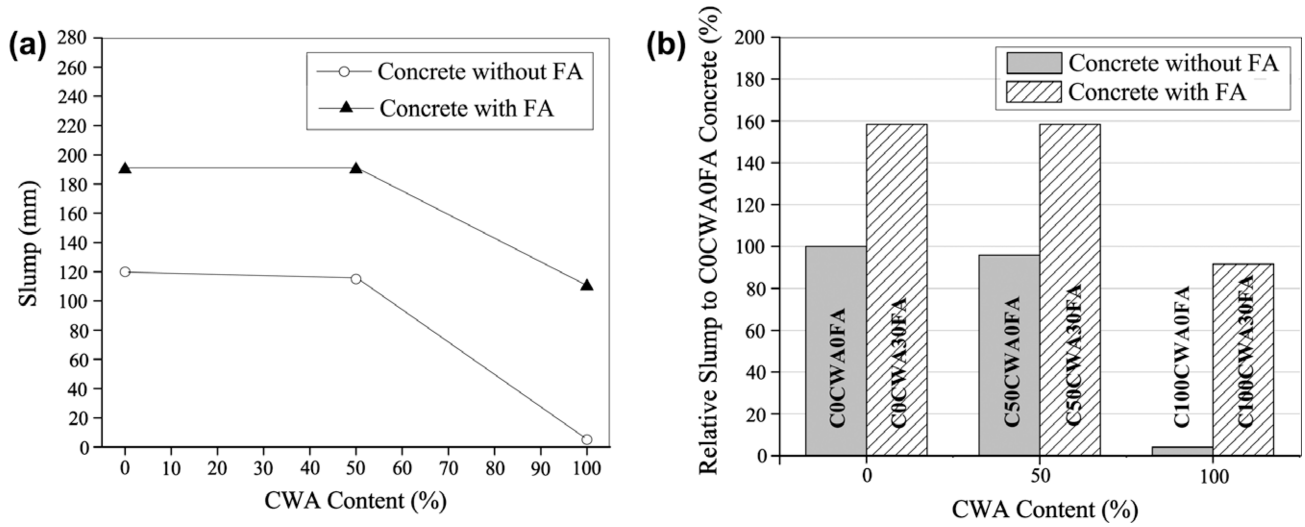

Fig. 8. The effect of CWA replacement as fine aggregates on the workability of concrete with and without FA: (a) slump and (b) relative slump.

reduction of slump was only 8.3% when the angular CWA was used at 50%.

3.4.2. Workability of concretes with fly ash

The effect of FA as Portland cement replacement at 30% by weight on the workability of concretes with CWA is shown in Fig. 8a. Relative workability of fly ash concretes is given in Fig. 8b. It can be seen that the trend of slump of FA concretes was similar to those of PC concretes, but with FA concretes having a higher slump throughout. Moreover, it is very interesting to note that when using 100% CWA to produce concretes, FA concrete still has a slump of 110 mm, which is similar to that of the control PC concrete (C0CWA0FA) of 120 mm. The reason for FA concrete exhibiting higher slump than concrete without FA is likely due to the direct influence of the smooth and round spherical surfaces of fly ash particles.

3.5. Compressive strength of mortars

3.5.1. Compressive strength of mortars without fly ash

The effects of CWA replacement as fine aggregates at 0%, 10%, 20%, 30%, 40%, 50% and 100% by weight on the compressive strength of mortars at 7, 14, and 28 days are shown in Fig. 9a. Relative strength of Portland cement mortars at 28 days is given in Fig. 9b. The results show that all mortar mixes containing CWA gave higher compressive strength than that of the control mortar (42.2 MPa at 28 days), and that the compressive strength increased with increasing use of CWA up to 50% by weight (50.2 MPa at 28 days). Bektas et al. [27] used crushed clay brick as fine aggregate replacement in mortars at 0%, 10% and 20% by weight and found that the compressive strength at 28 days of mortars with crushed clay brick were close to that of the control mix. In this study, the result shows that the compressive strength of mortar with 50% CWA increased by ≈18.9% compared to that of the control mortar. Previous research explained that the surface texture of the aggregate plays an important role in compressive strength of mortars [28,29]. The grip between the paste and the aggregate at the interfacial zone will be improved when a rougher texture aggregate is used, thereby leading to an increase in compressive strength [30]. This is consistent with the finding of this study, in which the compressive strength of mortar containing ceramic waste was higher than that of the control mortar. However, the compressive strength was found to decrease when CWA was used at 100% (45.8 MPa at 28 days). The rough and angular nature of CWA aggre-

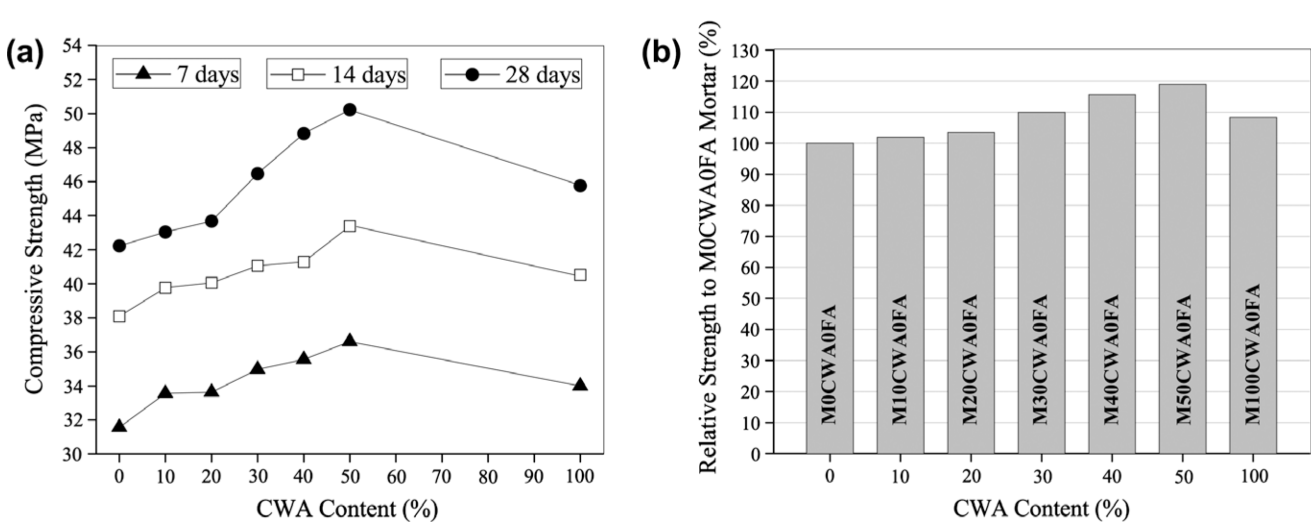

Fig. 9. The effect of CWA replacement as fine aggregates on the compressive strength of mortar without FA: (a) compressive strength and (b) relative strength.

gate affects the compaction of the mixes in the fresh state. Thus, a reasonable explanation for the decrease in strength when using CWA at 100% by weight may be due to the difficulty in the compaction of the harsh mortar.

3.5.2. Compressive strength of mortars with fly ash

The effect of FA as Portland cement replacement at 30% by weight on the compressive strength of mortars with CWA at 7, 14 and 28 days is shown in Fig. 10a. Relative strength of FA mortars at 28 days is given in Fig. 10b. The results show that compressive strength at 28 days of FA mortars containing CWA was higher than that of conventional FA mortar (M0CWA30FA). These increases in strengths of FA mortars with 50% CWA and 100% CWA were 19.6% and 19.3%, respectively. Again, this may be due to the enhanced overall interfacial zone due to the rougher and more angular shape of ceramic waste. In addition, it is very interesting to note that the results of compressive strength of mortars with FA differ from those of mortars without FA (Fig. 9a), since the compressive strength at 28 days of M100CWA30FA (35.4 MPa) was very similar to that of M50CWA30FA (35.5 MPa). This finding can be explained by the fact that FA, consisting of spherical and smooth particles, improved the flow of fresh mortar. Thus, mortar with FA was easier to compact than mixes without FA.

3.6. Compressive strength of concretes

3.6.1. Compressive strength of concretes without fly ash

The effects of CWA replacement at 0%, 50% and 100% by weight on compressive strength of Portland cement concretes at 7 and 28 days are shown in Fig. 11a. Relative strength of Portland cement concretes at 28 days is given in Fig. 11b. Past research works reported that there is a limit to the strength gain of concrete containing recycled aggregates [10,7,31]. Debieb and Kenai [18] reported that the compressive strength of concrete decreased with increasing use of crushed brick as fine aggregate replacement; the strength reduction for 100% by weight fine aggregate replacement was about 30%. This strength decrease could be due to the high water absorption of recycled fine aggregates. In this study, the compressive strength at 28 days of CWA concrete increased with the use of CWA at 50% by weight, where it reached optimum strength (40 MPa). This was an increase of 7.5% compared to the control concrete. Thereafter a decline in compressive strength was observed, with a slightly lower value (38.5 MPa) at 100% CWA. However, the compressive strength results with all percentages of CWA were observed to be higher than that of the control mix (37.0 MPa). A similar trend was observed at 7 days, where the optimum strength reached 29.5 MPa

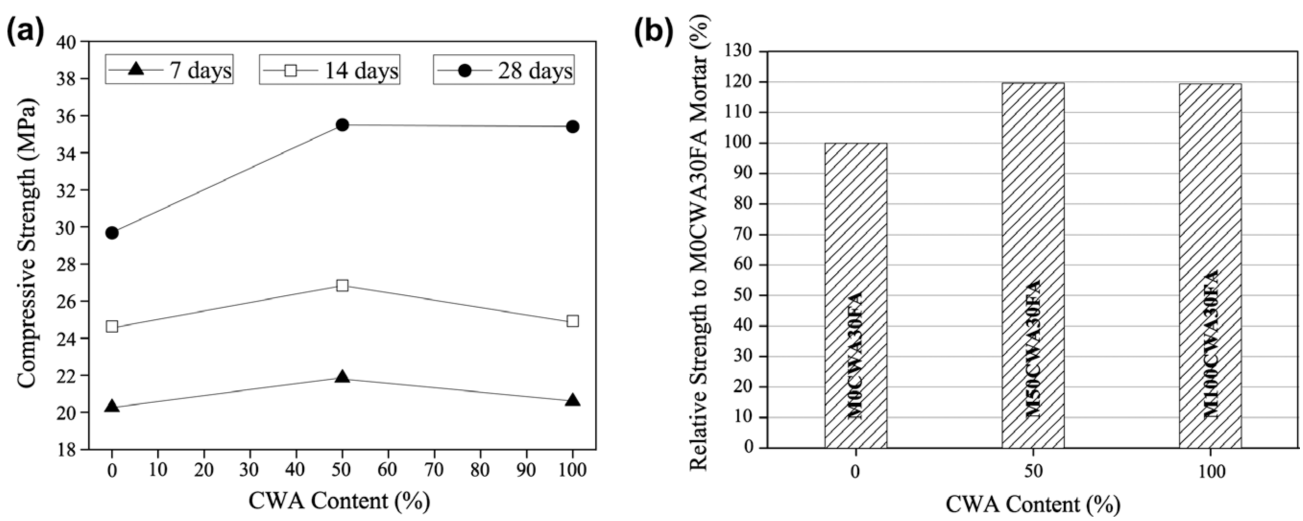

Fig. 10. The effect of CWA replacement as fine aggregates on the compressive strength of mortar with FA: (a) compressive strength and (b) relative strength.

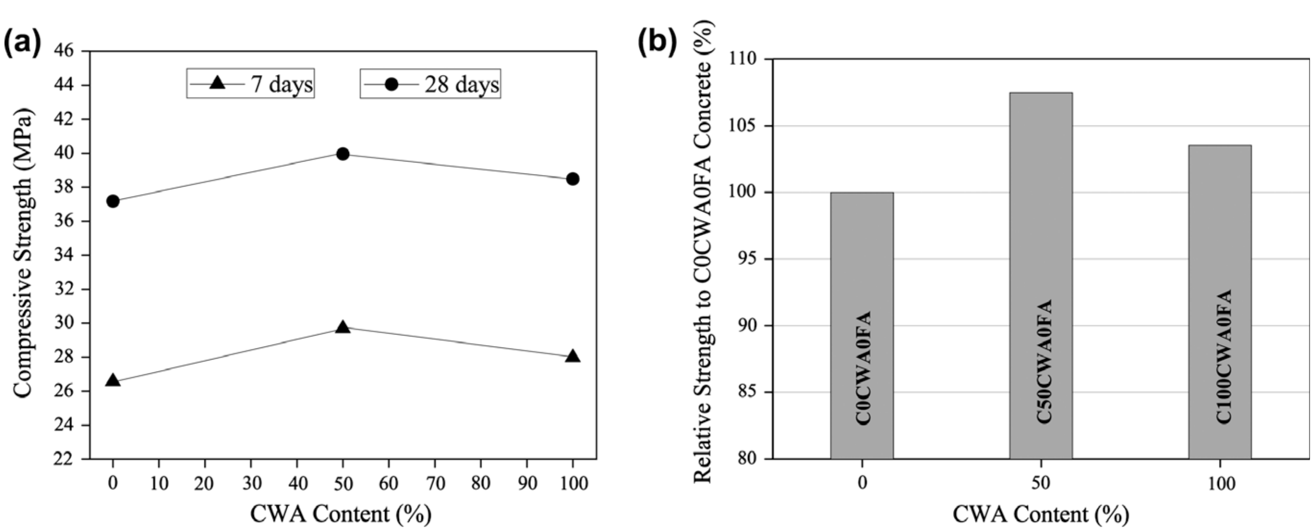

Fig. 11. The effect of CWA replacement as fine aggregates on the compressive strength of concrete without FA: (a) compressive strength and (b) relative strength.

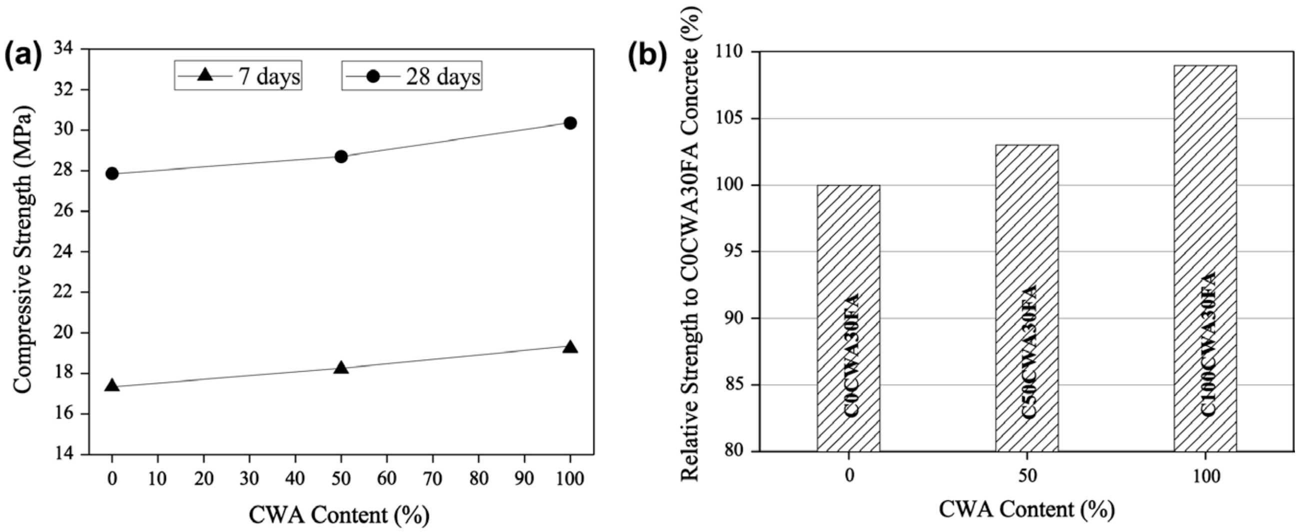

Fig. 12. The effect of CWA replacement as fine aggregates on the compressive strength of concrete with FA: (a) compressive strength and (b) relative strength.

when using CWA at 50%. This represents around a 12.0% gain compared to that of the control concrete. It is likely that the improved interfacial zone from the use of the rough ceramic, as well as the strength of the sintered ceramic (mullite), contributed to this increase in strength. This explanation is also consistent with previous research, which reported that aggregate texture plays an important role in the compressive strength of concrete [31].

Although the compressive strength of C100CWA0FA was noticed to be higher than that of the control mix (C0CWA0FA), the former mix was not workable in the fresh state (Fig. 8). The slight drop in strength when increasing the CWA content to 100% (C100CWA0FA) can be understood from the fact that the angular shape of CWA reduces the workability of concrete. Thus the concrete became much more difficult to compact, thereby resulting in lower strength than concrete with CWA at 50% (C50CWA0FA). This agrees with the slump test results reported earlier.

3.6.2. Compressive strength of concrete with fly ash

The effect of CWA replacement at 0%, 50% and 100% by weight on compressive strength of FA concrete at 7 and 28 days are shown in Fig. 12a. Relative strength of FA concrete at 28 days is given in Fig. 12b. The results were very interesting, in that the compressive strength of FA concrete, unlike the Portland cement control, was found to increase with CWA content, and was highest when using CWA at 100%. When CWA was used as sand replacement at 50% and 100% by weight, the compressive strengths of FA concretes at 28 days were 28.7 MPa and 30.4 MPa, respectively. This is an increase of approximately 3.0% and 9.0%, respectively, compared to C0CWA30FA (27.9 MPa).

In comparing the workability and strength results of both Portland cement control concrete and fly ash concrete, it is most likely that the workability played a very important role in the compressive strength results when using CWA. It was determined earlier that fly ash utilization with CWA gave an ideal balance to the

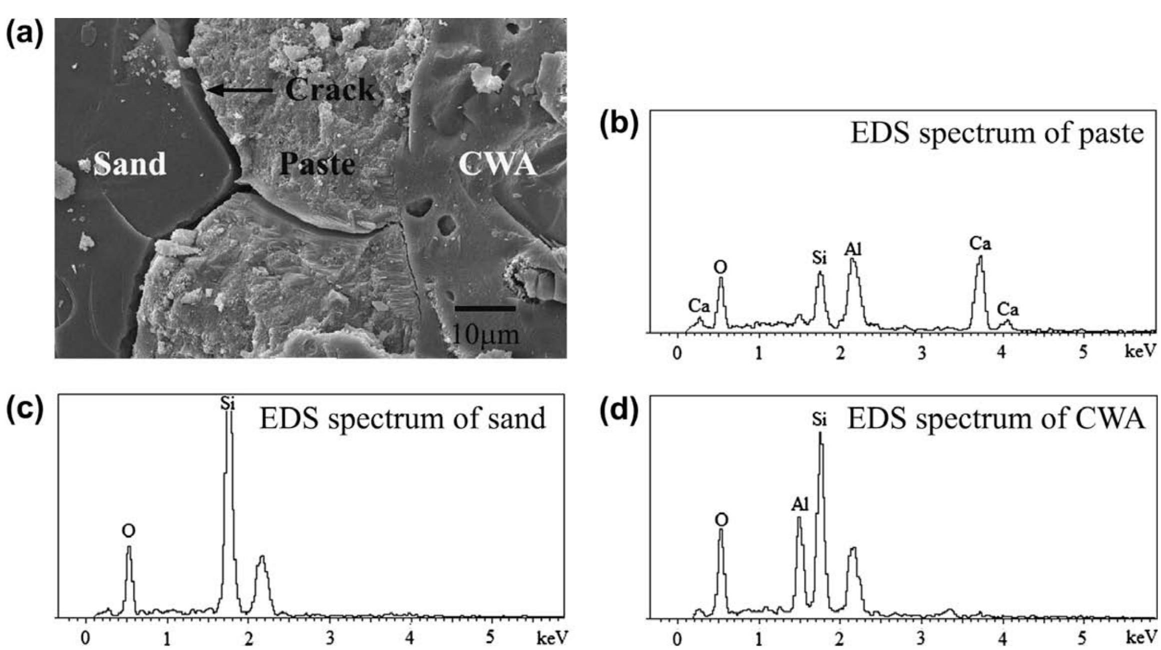

Fig. 13. Microstructure of specimen: (a) SEM, (b) EDS spectrum of paste, (c) EDS spectrum of sand, and (d) EDS spectrum of CWA.

workability, resulting in a continual increase in strength with CWA, and maintaining a workable concrete even when using CWA at 100%.

3.7. Microstructure

In considering the microstructure of specimens containing CWA at 50% by weight, small cracks were observed between the cement paste and sand particles (showing a smooth surface). Moreover, it is very interesting to find that there were no cracks between interfaces of CWA particles and cement paste (Fig. 13a). This finding is also consistent with the compressive strength test as reported earlier, in which the compressive strength of the specimen containing CWA was higher than that of the control mix. This was due to a rougher textured surface aggregate being used, hence improving the grip between the paste and the aggregate at the interfacial zone and thereby leading to an increase in compressive strength. EDS spectra of cement paste, sand and CWA can be seen in Fig. 13b–d, respectively. The cement paste spectrum consists of calcium, silicon, oxygen, and aluminum. In addition, EDS of sand reveals that sand is composed of silicon and oxygen, while CWA consists of silicon, aluminum, and oxygen, which are elements of the crystal structure of an aluminosilicate (mullite). These results are also in accordance with XRD analysis as shown in Fig. 4.

4. Conclusions

Based on this experimental investigation, it is feasible to use CWA as a sand replacement material to produce mortar and concrete with acceptable performance. The following conclusions can be drawn:

1. The mortar and concrete containing CWA generally exhibited a lower density than that of the control mix, due to the lower specific gravity of the CWA relative to natural sand.
2. The compressive strength of Portland cement mortar and concrete containing CWA was higher than that of the control mix due to a rougher surface of the CWA particles enhancing strength.
3. For concrete without FA, an increase in compressive strength was found up to a CWA content of 50% by weight. The slight drop in strength thereafter when increasing the CWA content to 100% can be understood from the fact that the angular shape of the CWA particles significantly reduced the workability of the concrete, making it much more difficult to compact, thereby lowering strength.
4. The compressive strength of fly ash concrete, unlike the Portland cement control concrete, was highest when using CWA at 100% substitution, as the utilization of fly ash with CWA gave an ideal balance to the workability, maintaining a workable concrete even when using CWA at 100%. This produced a continual increase in compressive strength with increasing CWA content.
5. It should be noted that further research work is now warranted to establish the effect of CWA as fine aggregates on the durability of concrete.

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References

[1] Malhotra VM, Mehta PK. Pozzolanic and cementitious materials. Advances in concrete technology, vol. 1. Gordon & Breach Publishers; 1996.
[2] Alonso JL, Wesche K. Characterization of fly ash. In: Wesche K, editor. Fly ash in concrete. London: E & FN SPON; 1991.
[3] Saraswathy V, Song HW. Evaluation of corrosion resistance of Portland pozzolana cement and fly ash blended cements in pre-cracked reinforced concrete slabs under accelerated testing conditions. Mater Chem Phys 2007;104(2–3):356–61.
[4] Zuquan J, Wei S, Yunsheng Z, Jinyang J, Jianzhong L. Interaction between sulfate and chloride solution attack of concretes with and without fly ash. Cem Concr Res 2007;37(8):1223–32.
[5] Miranda JM, Jimenez AF, Gonzalez JA, Palomo A. Corrosion resistance in activated fly ash mortars. Cem Concr Res 2005;35(35):1210–7.
[6] Ramamurthy K, Harikrishan KI. Influence of binders on properties of sintered fly ash aggregate. Cem Concr Compos 2006;28(1):33–8.
[7] Evangelista L, de Brito J. Mechanical behaviour of concrete made with fine recycled concrete aggregates. Cem Concr Compos 2007;29(5):397–401.
[8] Jo B, Park S, Park J. Properties of concrete made with alkali-activated fly ash lightweight aggregate (AFLA). Cem Concr Compos 2007;29(2):128–35.
[9] Rajamane NP, Annie Peter J, Ambily PS. Prediction of compressive strength of concrete with fly ash as sand replacement material. Cem Concr Compos 2007;29(3):218–23.
[10] Tang WC, Lo Y, Nadeem A. Mechanical and drying shrinkage properties of structural-graded polystyrene aggregate concrete. Cem Concr Compos 2008;30(5):403–9.
[11] Poon CS, Chan D. Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. Constr Build Mater 2006;20(8):578–85.
[12] Choi YW, Moon DJ, Chung JS, Cho SK. Effects of waste PET bottles aggregate on the properties of concrete. Cem Concr Res 2005;35(4):776–81.
[13] Kou SC, Poon CS. Properties of self-compacting concrete prepared with recycled glass aggregate. Cem Concr Compos 2009;31:107–13.
[14] Senthamarai RM, Devadas Manoharan P. Concrete with waste aggregate. Cem Concr Compos 2005;27(9–10):910–3.
[15] Oikonomou ND. Recycled concrete aggregates. Cem Concr Compos 2005;27(2):315–8.
[16] De Brito J, Pereira AS, Correia JR. Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates. Cem Concr Compos 2005;27(4):429–33.
[17] Gomes M, De Brito J. Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance. Mater Struct 2009;42(5):663–75.
[18] Debieb F, Kenai S. The use of coarse and fine crushed bricks as aggregate in concrete. Constr Build Mater 2008;22(5):886–93.
[19] Senthamarai RM, Devadas MP. Concrete with waste aggregate. Cem Concr Compos 2005;27(9–10):910–3.
[20] ASTMC C33. Standard specification for concrete aggregates. Annual book of ASTM standards, vol. 04.02. Easton; 1993.
[21] ASTM C 948-81. Standard test method for dry and wet bulk density, water absorption, and apparent porosity of thin sections of glass–fiber reinforced concrete. Annual book of ASTM standards, vol. 04.05. Easton; 1993.
[22] ASTM C 1437-99. Standard test method for flow of hydraulic cement mortar. Annual book of ASTM standards, vol. 04.01. Easton; 2000.
[23] ASTMC143/C 143M-98. Standard test method for slump of hydraulic-cement concrete. Annual book of ASTM standards, vol. 04.02. Easton; 2000.
[24] ASTMC192. Standard test method for making and curing concrete test specimens in the laboratory. Annual book of ASTM standards, vol. 04.02. Easton; 2000.
[25] Payá J, Monzó J, Borrachero MV, Peris-Mora E, González-López E. Mechanical treatment of fly ashes part II: particle morphologies in ground fly ashes (GFA) and workability of GFA–cement mortars. Cem Concr Res 1996;26(2):225–35.
[26] Ismail ZZ, AL-Hashmi EA. Use of waste plastic in concrete mixture as aggregate replacement. Waste Manage 2008;28(11):2041–7.
[27] Bektas F, Wang K, Ceylan H. Effects of crushed clay brick aggregate on mortar durability. Constr Build Mater 2009;23(5):1909–14.
[28] Westerholm M, Lagerblad B, Silfwerbrand J, Forssberg E. Influence of fine aggregate characteristics on the rheological properties of mortars. Cem Concr Compos 2008;30(4):274–82.
[29] Özkan Ö, Yüksel İ. Studies on mortars containing waste bottle glass and industrial by-products. Constr Build Mater 2008;22(6):1288–98.
[30] Neville AM. Properties of concrete. Harlow: Addison Wesley Longman Limited; 1997.
[31] Taha B, Nounu G. Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement. Constr Build Mater 2008;22(5):713–20.