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Eco-efficient concrete containing recycled ceramic wastes aggregate

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Abstract. The construction industry is in search of cleaner and greener alternatives for materials in concrete. The main objective of this study was to determine the properties of concrete using recycled ceramic waste aggregates (CWA). In this study, natural fine and coarse aggregates were partially substituted as ceramic waste aggregate in the range of 25%, 50% and 75%. Fifty-four cubes and twenty-one cylinders were prepared and tested to obtain the physical and mechanical properties of concrete. The compressive strength of concrete specimens containing 50% recycled ceramic fine aggregates (CFA) and 75% recycled ceramic coarse aggregates (CCA) is greater than the conventional concrete. However, the modulus of elasticity decreased with increased recycled aggregate content. The aggregates replacement decreases the concrete density but satisfying the desired compressive strength of concrete. The results made it possible to adopt ceramic tile waste as recycled aggregate materials to promote sustainable development in the production of concrete.

1. Introduction

The construction industry is in search of cleaner and greener alternatives for materials used in concrete to provide a sustainable environment in materials construction. Reduction of natural resources and the high cost of construction materials lead to finding another source of waste material in the production of concrete. Ceramic tile waste is among the material which has a high potential as aggregate replacement in concrete production. In the ceramic tile production, residues may occur due to size discrepancies, glazing faults, cracks, and unfortunate firing result [1]. The quantity of such non-standard or rejected tiles can be up to 7% of the manufacturing capacity of the factories [2]. Ceramic waste materials have been classified as non-biodegradable waste because biodegradation period of ceramic is very long and can be up to four thousand years [3]. Thus, the utilization of these waste material will be beneficial to the construction sector as environmentally friendly material in concrete. The prospects of ceramic tile manufacturers in Malaysia are generally healthy on the back of the still substantial property and construction sectors in the country that is driving demand for building materials. There are still many construction projects and property development activities going on in the country which help sustain domestic demand growth for ceramic tiles industry. The value of construction work done in the fourth quarter 2018 recorded an increase of 4.1% year-on-year to record RM36.5 billion resulted from positive

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growth in the civil engineering, special trades activities, construction of the residential and non-residential building [4]. Furthermore, this will generate an enormous ceramic tile waste due to the high demand for ceramic tile in the construction sector. Although the recent study has confirmed that ceramic waste materials have a high potential as aggregates replacement in concrete, however, there is still a lack of research on the use of ceramic tile waste in Malaysia. The objectives of this study were to compare the properties of ceramic waste aggregate (CWA) and the natural aggregate and to investigate the effect of CWA to the engineering properties of concrete. In this study, ceramic tile wastes were adopted as recycled fine and coarse aggregate replacement in concrete production to promote sustainable development in the production of concrete.

Utilization of ceramic wastes aggregate (CWA) is not new research in the production of eco-efficient concrete. Many good references on the present study relate to the use of ceramic tile as an aggregate replacement in concrete [1], [5]–[11]. Ceramic sanitary ware is among the ceramic waste which has a potential as an aggregate replacement in concrete [12]–[15]. In the meantime, reusing ceramic waste from electric insulator and brick material results promising concrete properties [16]–[19]. Besides, mixed recycled ceramic and ceramic brick waste from construction and demolition are being utilized in concrete production [20], [21].

The aggregates properties of CWA are different compares to natural aggregates. Natural aggregates are naturally formed while ceramic product produced through several processes includes forming the shape and firing in high temperature [22]. As a result, CWA has lower density and specific gravity compares to the natural aggregates [11], [16], [17]. The CWA particularly ceramic tile usually has a smooth and glazed surface and uneven shape [1], [5]. The way of an aggregate which is not even, flat, and has a smooth surface will influence the workability and capability of the concrete. Usually, an elongated and flaky aggregate will quickly go through failure compared to an aggregate which is even. When hit with pressure, the potential for the elongated aggregate to crack or break is higher compared to an even-sized aggregate. The shape and flakiness of CWA are more elevated than natural aggregates and lead to a weak adhesion between the ceramic aggregates and cement paste [1]. The aggregate surface revealed clean and glazed effect after concrete failure. Also, some of the CWA were easily pulled out due to the impact of the smooth surface, shape angularity and the water absorption of the ceramic waste aggregate which lead to bonding failure in concrete [5].

Adopting ceramic waste in concrete also influence the properties of concrete. In general, workability of concrete containing CWA is lower than the conventional concrete [7]. The workability of concrete reduced with the increased in amount in ceramic waste [1], [11]. The quite higher water absorption and also being more angular of aggregates decreases the workability concrete [8], [10]. When mixing the concrete, it is necessary to add more water to achieve the desired consistency [15], [18]. Presoaking the CWA may overcome the workability concern; however, presoaking the CWA may also increase slump due to the excessive water on the surface of CWA [5]. Furthermore, the density of concrete reduces and declines linearly with rising replacement rates [8], [13], [18], [21]. The reduction in concrete density is due to the higher porosity and lower bulk density of CWA compared to natural aggregates [15] hence cause the ultrasonic pulse velocities to decrease with an increase in CWA content [10]. However, the density of concrete is within the safe limits of normal weight concrete [11].

The mechanical behavior of CWA concrete depends on the types of CWA used in concrete [1], [13]. In most cases, the concrete strength satisfies the desired compressive strength, and no harmful influence compare to the reference concrete [5], [14], [17]. The mechanical properties of CWA concretes improved as the replacement percentage of natural aggregates increased [7], [12], [21]. One side of CWA aggregate is very rough and porous, which may be due to the presence of clay, whereas another side of aggregate is glassy and less porous. The strong bond may be established at the rough and porous surface, which allowed the hydrated products to penetrate inside and contribute to chemical anchorage [11]. The unique bond, a higher strength of CWA relative to the natural aggregates and a possible pozzolanic effect of CWA, also improving the compressive strength of concrete [15]. On the other hand, the compressive strength decrease as the CWA content increased [6], [10], [18]. The presence of flaky and smooth surface of CWA may decrease the compressive strength due to the lack of engagement of aggregates and concrete [8]. Increase in CWA content generally decreases the modulus of elasticity [1], [10], [18]. The reduction of modulus of elasticity observed in the CWA concrete is mainly due to their high porosity result in lower stiffness than the natural aggregates [13]. The modulus of elasticity decreases typically with increasing recycled aggregate content, the degree of which depends on characteristics inherent to recycled aggregate, i.e. type, replacement level, size and quality of the original material [23].

2. Methodology

In this study, ceramic tile wastes were collected from industrial waste in Pasir Gudang (Johor, Malaysia) and crushed using a jaw crusher to obtain fine and coarse aggregates into particles of 4.75mm and 10mm, respectively. The CWA is prepared to the size not exceeding 10mm intended to decrease the effect of smooth surface, flakiness and increase rougher surface area. Natural aggregates were replaced by CWA at 25%, 50% and 75% as fine and coarse aggregates separately. Table 1 shows the composition of the concrete mix. In this study, no replacement of the fine along with the coarse aggregate due to minimal effect on the mechanical behaviors [5]. All mixtures had a target slump of 60-180 mm to maintain a desirable level of workability. Consequently, the w/c used was 0.55 however, since more water absorbed by CWA, additional water permitting to the percentage of water absorption of the recycled aggregate is added to maintain the workability. Fifty-four cubes measured (100 x 100 x 100) mm and twenty-one cylinders (100 x 200) mm were prepared and tested to obtain the physical and mechanical properties of concrete.

Table 1. Mix proportion of concrete

Mix no.	Cement (kg/m^3)	Water (kg/m^3)	Fine aggregate		Coarse aggregate	
			Normal sand (kg/m^3)	CFA (kg/m^3)	Granite (kg/m^3)	CCA (kg/m^3)
RC	455	250	800	-	835	-
CFA25	455	253	600	200	835	-
CFA50	455	256	400	400	835	-
CFA75	455	259	200	600	835	-
CCA25	455	253	800	-	625	210
CCA50	455	256	800	-	420	420
CCA75	455	259	800	-	210	625

*RC-reference concrete, CFA-ceramic fine aggregates, CCA-ceramic coarse aggregate

3. Result and discussion

Table 2 shows the properties of CWA and natural aggregates. The natural aggregate had a specific gravity of 2.6. The CWA presented a lower specific gravity, standing at 2.2. In general, CWA is slightly weaker than the natural aggregate. The CWA shows much higher water absorption than the natural aggregate which agreed with the previous work [1], [5], [11]. The CWA shows better performance on the impact resistance compares to NCA and in line with the results obtained by Rashid *et al*. (2017). The natural aggregate had a flakiness index of 15.6% while CWA presented higher flakiness index at 21.7 %. The elongation index of the natural aggregate significantly differs from that of CWA. The shape of the natural aggregate had an elongation index at 25.9% compared to CWA at 16.7%. The limitation of the size of coarse aggregate to 10mm provide good appearance in shapes and reduce the angularity of aggregates.

Table 2. Basic properties of CWA and the natural aggregates

References	Aggregate Properties	Natural aggregate	CWA
(ASTM C 127)	Specific gravity	2.6	2.2
(ASTM C 127)	Water absorption, %	1.4	4.9
(BS812-112:1990)	Aggregate Impact Value (AIV), %	19.3	18.8
(BS812-105.1:1989)	Flakiness Index, %	15.6	21.7
(BS812-105.2:1990)	Elongation Index, %	25.9	16.7

Figure 1 shows the relative concrete workability of all concrete mixes. The workability shows a linear increase in the CFA series. This result is in contrast with the result obtained by Topçu and Bilir (2010), Awoyera *et al.*(2016), and Alves *et al.* (2014). Adopting CWA in the substitutions of river sand lower the stiffness and result in less cohesion in the concrete mix. The slump is slightly higher for all CFA series, standing at 3%, 14% and 22% respectively. In general, linear decreases on the workability for CCA series, standing at 0%, 5% and 7% respectively. The addition of more significant water in concrete mixes to overcome the high water absorption in CWA resulting in similar consistency in all blends. The result obtained agreed with Lucas *et al.* (2016) and Martínez-Lage *et al.* (2012). Nevertheless, all the measured slump satisfies the targeted slump in the design mix.

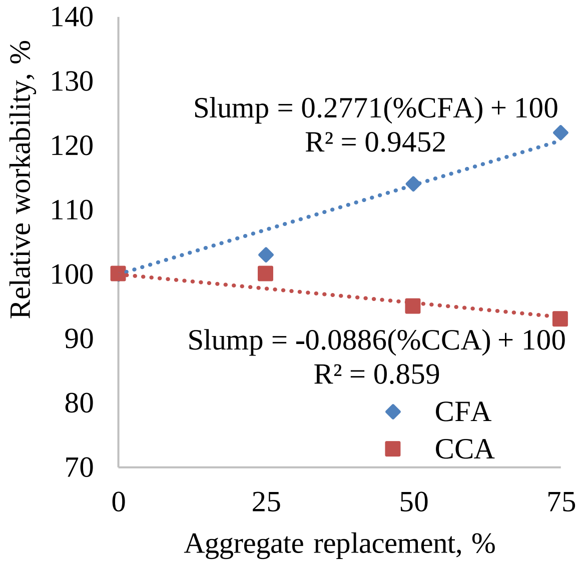

Figure 1. Workability of concrete

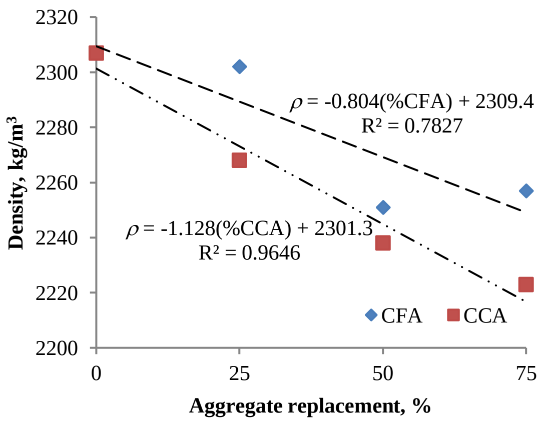

Figure 2. Concrete density

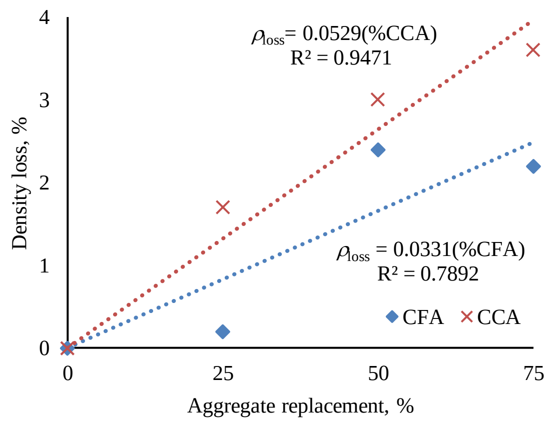

Figure 3. Density loss

Figure 2 shows the concrete density versus the replacement rate, confirms that density linearly decreases as the percentage of ceramic replacement increased. The CCA series show lower density compare to CFA series. However, the density of concrete for both CCA and CFA series are within the density range for normal-weight concrete. Figure 3 shows the density loss in the both CCA and CFA series. Density loss inclined approximately linearly with rising replacement rates. The maximum density loss for CFA and CCA series was 3.6% and 2.2% respectively. The concrete quality for all series tested presented in Table 3. The values generally showed good concrete quality for all specimens. The ultrasonic pulse velocities (UPV) decrease with an increase in CWA content. This result agreed with Topcu and Bilir (2010). The CFA50 and CCA75 series show more significant UPV result compare to the reference concrete. However, it was a minor improvement with 1.6% and 0.9% respectively.

Table 3. Concrete quality

Mix no.	Average UPV, km/sec	Concrete quality
RC	4.38	Good
CFA25	4.22	Good
CFA50	4.45	Good
CFA75	4.22	Good
CCA25	4.32	Good
CCA50	4.23	Good
CCA75	4.42	Good

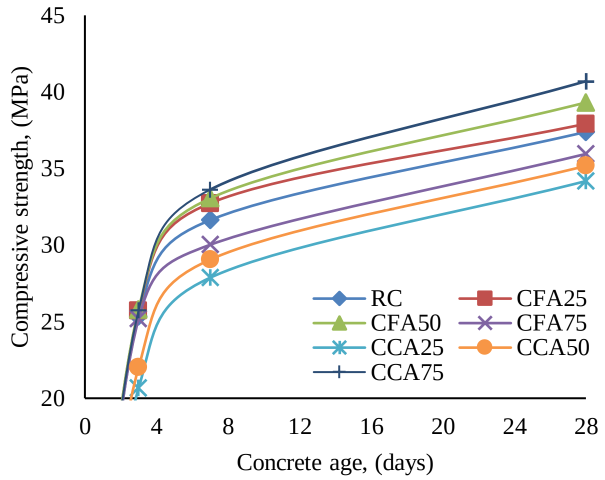

Figure 4. The average of cube compressive strength

The compressive strength presented in Figure 4 conducted to BS 1881-116:1983[28]. As can be seen, the compressive strength for all series increased by the ages of concrete. The strength development was similar, and uniform for all series tested, showing that the specimen prepared consistently. All series tested to achieve the desired characteristic compressive strength and in agreement with the results reported by Anderson *et al*. (2013). The series of CFA25, CFA50, and CCA75 shows higher compressive strength compares to the reference concrete. In contrast, the series of CFA75, CCA25, and CCA50 shows lower compressive strength. The compressive strength increased 1% and 5% for CFA25 and CFA50 respectively, however, decrease 4% for CFA75. In the meantime, lower compressive strength recorded at 9% and 6% for CCA25 and CCA50 but 9% higher for CCA75 series. Hence, the fine and coarse aggregate replacement giving greater concrete strength was 50% and 75% respectively. The dispersion of CFA50 and CCA75, shown in Figure 5. It can be seen that the dispersion of CWA in both CFA50 and CCA75 are quite uniform and shows good interlocking between the aggregate particles. Rashid *et al*. (2017) confirm that the weakest zone in concrete is the interface between an aggregate and a cement paste known as interfacial transition zone (ITZ). Although the CWA is flakier than the natural aggregate, however, achieved comparable concrete strength. In the CCA series, minimization of the coarse aggregate size to reduce the smooth surface effect and delivers a rougher surface results greater bonding in the ITZ hence contributes to the higher compressive strength.

(a) RC (b) CFA50 (c) CCA75

Figure 5. Dispersion of ceramic waste aggregates

The static modulus of elasticity presented in Figure 6 conducted to BS 1881-121:1983[29]. As can be seen, the modulus of elasticity for both CFA and CCA series decrease as the aggregate content increased. The reference concrete, RC found to the highest modulus of elasticity while the CFA75 and CCA75 series recorded the lowest value. The modulus of elasticity for all specimens tested varies from 13 GPa to 22 GPa. Although CWA may exhibit comparable compressive strength to corresponding to natural aggregate mixes, as the CWA content increases the modulus of elasticity decreases. The result obtained agreed with the previous work [9], [13], [23]. The high water absorption and the quality of CWA used in this study appear to influence the modulus of elasticity.

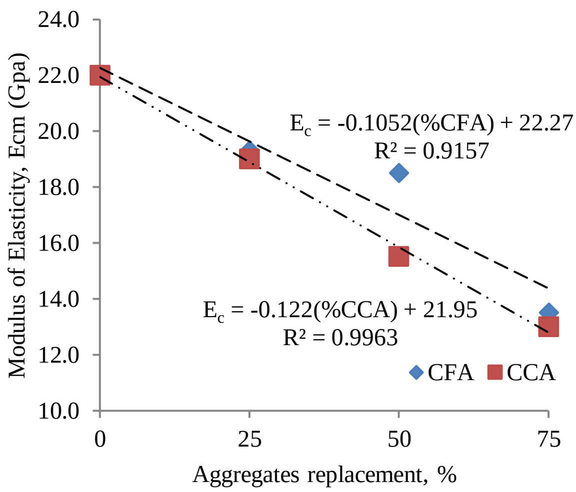

Figure 6. Modulus of elasticity

4. Conclusion

The utilization of the CWA in concrete production is undoubtedly feasible with promising results obtained in this study. The conclusion drawn from the present study are as follows:

- The aggregates properties between CWA and natural aggregate showing comparable properties except for the flakiness and shape of aggregates.
- The adoption of CWA in substitution with the natural aggregate satisfies the desired workability level. The density decrease as increased of CWA content. The CWA concrete achieved a good concrete quality for all specimens tested.
- All series tested proved to gain the desired characteristic compressive strength. The CWA replacement giving greater concrete strength was 50% and 75% for fine and coarse aggregate respectively.
- The modulus of elasticity decreases typically with increasing CWA content, the degree of which depends on characteristics inherent to the water absorption and the quality of the original material.

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