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Influence of Industrial Ceramic Waste Aggregates on Elastic Properties of Concrete

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Abstract: The deficiency of the natural resources has forced the construction sectors for the exploration of cleaner and greener materials-based concretes. The utilization of the recycled aggregates has emerged as an encouraging option to promote the sustainable production of these concretes. However, for the diverse structural applications of such green concretes their elastic traits must be assessed and designated. In this view, new type of concrete mixes were designed using the recycled ceramic waste aggregates (CWA) and their elastic properties were evaluated. The naturally occurring fine and coarse aggregates replaced with the CWA at various levels (25%, 50%, and 75%) were used to prepare the concrete mixes. The physical and mechanical properties of 54 cubical and 21 cylindrical concrete specimens were determined. The results show that aggregates replacement was found to reduce the density and enabled to accomplish the desired compressive strength of the proposed concretes. The compressive strength of the CWA concrete was equivalent to that of the control concrete. Moreover, the elastic modulus of the concretes was found to decrease with the increase in the CWA contents. It is seen that ceramic tile wastes have the potential to be used as recycled aggregate in concrete.

Keywords: ceramic waste aggregates, recycled aggregates, modulus of elasticity

1. Introduction

In recent years, the construction industries worldwide are in constant search for the cleaner and greener materials for the production of concretes. This is mainly due to the rapid depletion of the natural resources and the high cost of the construction materials. The use of various recycled aggregates as the effective replacement material of the natural aggregates in the production of the concrete became most viable. In fact, certain recycled materials from the construction and demolition activities have been offering to attain a better sustainability in the civil engineering sectors with environmental friendliness. Several studies have been conducted related to the construction and demolition

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wastes-based recycled aggregates to achieve low cost and high performing green concretes [1]-[9]. However, it requires a long time to obtain the resources from the demolition activities. In addition, the construction industries are often utilizing both natural and recycled materials excessively to control the cost of the construction. Meanwhile, the ceramic tile wastes are generated almost every day due to poor handling, transportation faults, and unsold stock clearance and shortages in the production line. The occurrences of the defects in the ceramic tile production may be due to the size discrepancies, glazing faults, cracks, and improper firing [10]. Generally, the amount of such substandard or rejected ceramic tiles from the factories is approximately 7% of the annual manufacturing capacity [11]. These abandoned ceramic tiles have been listed as the non-biodegradable waste because their period of biodegradation is very long which can be up to 4000 years [12]. Thus, the utilization of the ceramic waste aggregates (CWA) turned out to be beneficial to the building sectors as an environmentally friendly material for the concrete production.

Despite the disclosure that the CWA are highly potential as the replacement materials in the concrete, but they possess very different characteristics and attributes compared to the natural aggregates. Based on the manufacturing process, the ceramics can be produced via different processes including the shape forming, combustion, melt-quenching, annealing and firing at high temperatures [13]. It was reported that, the ceramic waste aggregates have lower densities and specific gravity compared to the natural aggregates [14]-[16]. The CWA (mainly the ceramic tiles) has smooth and glazed surfaces with irregular shapes [10], [17]. Usually, the failure rates of the elongated and flaky aggregates are much higher compared to the round shaped. Under the heavy load or pressure, the elongated aggregates can crack or break more easily than those with regular shape. In short, the higher shape elongation and flakiness of the CWA than the natural aggregates is responsible for the weak adhesion and strength between the ceramic aggregates and cement paste which need to be considered in the design [10].

The ceramic wastes can be classified into different categories depending on the source of the raw materials. The fired waste products including the bricks, blocks, and roof tiles belong to the first category that is generated by the structural ceramic factories using the red pastes only. The stoneware ceramics such as the wall, floor tiles, and sanitary wares belong to the second category that is produced from the fired wastes [18]. Thus, the mechanical traits of the CWA-based concretes may differ depending on the preparation processes of the ceramic products [10], [19]. Usually, the strength of the CWA-based concretes satisfy the desired compressive strength criteria without any harmful influence compared to the control concrete [16], [17], [20]. Some studies on the elastic properties of the CWA-based concretes revealed a decrease in the elastic moduli with the increase in the contents of the recycled aggregates [10], [21], [22]. Meanwhile, the concretes made from the recycled aggregates (RA) obtained from the construction and demolition activities showed lower elastic moduli with the increase in RA contents. The elastic moduli of these recycled aggregates-based concretes were found to be affected by the level of the replacement, aggregates size, quality of the original material, and mixing procedures. All these factors may lead to the high porosity in the produced concrete, resulting in the lower stiffness than the natural aggregates [19], [23].

In the designation of the structural concrete, the modulus of elasticity plays a vital role for the serviceability limit state, controlling the deformation of the concrete. Therefore, the reduction in the elastic modulus leads to the stiffness loss of the structural concrete elements. In order to overcome such limitation, the ceramic tile wastes were used as the recycled fine and coarse aggregates replacement in the concrete production to promote the sustainable development of the new types of concretes. The produced CWA-based concretes were characterized to determine the influence of various CWA contents on their strength and elastic properties. The experimental results were analyzed to assess the stiffness level of these CWA-based concretes.

2. Methodology

The ceramic tile wastes (Fig. 1) were collected from a local industry (Johor, Malaysia) and crushed using a jaw crusher to obtain fine aggregates (CFA) and coarse aggregates (CCA) of particles size 4.75 mm and 10 mm, respectively. In order to enhance the surface roughness together with the reduced smoothness and flakiness of the prepared CWA, their sizes were kept at 10 mm or less. The use of CWA at different contents (25, 50 and 75%) as the CFA and CCA were used separately to replace part of the natural aggregates (NA). Table 1 shows the composition of the proposed concrete mixes where no replacement of the fine and coarse aggregates together was done due to the minimal effect on the mechanical behaviors of the produced concretes [17]. All the concrete mixes were designed for the slump of 60-180 mm to maintain the desirable level of workability. The water to cement ratio (w/c) was maintained to 0.55 because more water is absorbed by the CWA. The amount of water calculated to cater for the water absorption of the recycled aggregates was added to maintain the workability of the mixes. A total of 54 cubical (dimension of 100 mm × 100 mm × 100 mm) and 21 cylindrical (diameter by length of 100 mm × 200 mm) shaped concrete specimens were prepared and tested to determine their physical and mechanical properties.

The modulus of elasticity of the prepared concretes (CCA- and CFA-based) specimens shown in Fig. 2 was measured using an electrical strain gauge (under the axial loading rate of 0.006 mm/s) and extensometer-compressometer instruments in accordance with BS 1881-121:1983 [30]. Irrespective of the concrete series, the modulus of elasticity measured using the electrical strain gauges was slightly higher compared to the one obtained via the extensometer setup. In this test, an electrical strain with gauge of length 60 mm was bonded adequately in the middle of the cylindrical specimen. The bonded electrical strain gauge was a standard procedure placed in the elastic region to generate the high quality and reliable strain output [31]. However, due to the absence of bonding between the strain gauges and the specimen in the plastic region no reliable strain reading was obtained. Conversely, the concretes strain measured by the extensometer technique was both time and cost saving. In addition, this approach demonstrated relatively lower variability to the measured strain values. The extensometer provided the average extension around 100 mm, and thereby mostly failed to provide any variation of the localized strains in the concretes. Meanwhile, the strain gauge yielded the average strain measured through a gauge length of the strain gauge. It can be said that the method of the strain measurement and the level of the sensitivity of both techniques produced different reading in the modulus of elasticity.

Table 1 – The composition, mix proportions and codes of the prepared concretes

Mix code	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	250	600	200	835	-
CFA50	455	250	400	400	835	-
CFA75	455	250	200	600	835	-
CCA25	455	250	800	-	625	210
CCA50	455	250	800	-	420	420
CCA75	455	250	800	-	210	625

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

Fig. 1 – The photograph of the ceramic tile wastes

Fig. 2 – Elastic modulus measurement setup

3. Results and Discussion

Table 2 displays the measured physical properties of the CWA and NA (specific gravity of 2.6) with their reference standards. The CWA showed approximately 15% lower specific gravity and much higher water absorption than the NA which is consistent with the previous reports [10], [14], [17]. In addition, the current CWA revealed better impact resistance compared to the natural coarse aggregates which is in good agreement with other work [14]. The flakiness index of the CWA was nearly 39% higher than the NA and the elongation index of the CWA (16.7%) was significantly lower than the NA (25.9%). The size restriction of the CWA (≤ 10 mm) imparted their good shape appearance and reduced angularity.

Table 2 - Basic physical properties of the CWA and NA

References	Aggregates properties	Natural aggregates	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

Table 3 depicts some of the measured physical and mechanical characteristics of the proposed concretes. The overall properties of the produced concretes were significantly affected due to the inclusion of the CWA into the mixes. The workability of the concretes was increased linearly with the increase in the CFA contents which showed a deviation from the other findings [19], [21], [28]. The use of CWA as the substitute of the river sand resulted in a lower stiffness and less cohesion of the concrete mixes. The slump was slightly higher for all CFA-based concretes compared to the control specimen in the range of 3 to 22%. The workability of the three CCA-based concretes was decreased linearly (0%, 5%, and 7%) with the increase in the amount of CWA contents. The observed reduction in the workability of the proposed concretes was attributed to the reasonably higher water absorption and more angular shape factor of the aggregates. The amount of water added to the concrete mixes was based on their percentage of absorption and the purpose was to overcome the problem of high-water absorption by CWA, achieving similar consistency of all concrete mixes. The results on the slump traits were agreed with the other literature reports [22,29]. Nevertheless, all the measured slump satisfied the targeted slump of the designed mixes.

The density of the concretes were linearly decreased with the increase in the level of replacement which was probably due to the higher porosity and lower bulk density of the CWA compared to the NA [29]. The CCA-based concretes showed lower density compared to the CFA-based concretes (Table 3). However, the densities of both series of the concretes were within the range of the normal-weight concrete. The maximum density loss of the CFA and CCA-based concretes was 2.2% and 3.6%, respectively. The results of ultrasonic pulse velocity (UPV) test confirmed the good quality of all the specimens. The measured value of UPV of the concretes were decreased with the increase in the CWA content (Table 3) which is highlighted also by the earlier report [21]. The CFA50 specimen disclosed slightly higher UPV (1.6%) compared to the RC.

The measured compressive strength (fc_{cube} and $fc_{cylinder}$) of both CFA and CCA-based concrete series were in conformity with the other reports [17]. In general, the CFA25, CFA50, and CCA75 specimens showed higher compressive strength compared to the control concrete (Table 3). The compressive strength of the CFA-based concretes (fc_{cube} and $fc_{cylinder}$ were decreased with the increase of CWA contents) exhibited reverse behavior to the CCA-based concretes (fc_{cube} and $fc_{cylinder}$ were increased with the increase of CWA contents). These behaviors were possibly attributed to the surface properties of the CWA where one side was very rough and highly porous, may be due to the presence of the clay, and the other side was glassy and less porous. In addition, the generation of the strong bonds on the rough and porous surfaces enabled the hydrated cement products to penetrate inside the voids, thereby contributing to increase bond strength. Consequently, the formation of such unique chemical bonds imparted a higher strength and possible pozzolanic effect to the CWA relative to the NA, thus improving the compressive strength of the proposed concretes [29]. In contrast, the CFA75, CCA25, and CCA50 specimens displayed varies in compressive strength. The compressive strength of the CFA25 and CFA50 specimen was correspondingly increased by 1% and 5%, respectively, and for the CFA75 mix decreased by 4%. The results revealed that the fine and coarse aggregates replacement into the mixes imparted the highest compressive strengths at the 50% and 75%, respectively.

Table 3 - Some measured physical and mechanical properties of the produced concretes

Mix code	Slump (mm)	Density (kg/m^3)	Density loss (%)	UPV (km/sec)	fc_{cube} (MPa)	$fc_{cylinder}$ (MPa)
RC	100	2307	0.0	4.4	37.39	31.23
CFA25	103	2302	0.2	4.2	37.92	34.28
CFA50	114	2251	2.4	4.5	39.31	34.88
CFA75	122	2257	2.2	4.2	35.95	29.22
CCA25	100	2268	1.7	4.3	34.18	32.79
CCA50	95	2238	3.0	4.2	35.17	34.22
CCA75	93	2223	3.6	4.4	40.70	36.83

The modulus of elasticity (Fig. 3) for both CFA and CCA-based concretes were decreased with the increase in the aggregates content. The control concrete recorded the highest modulus of elasticity, while the CFA75 and CCA75 specimen showed the lowest value. The modulus of elasticity for all specimens was varied from 10 GPa to 27 GPa. Although the CWA exhibited a comparable compressive strength to the corresponding NA, but the lower modulus of elasticity of the CWA was responsible for the higher deformation of the produced concretes. These similar results also reported in the previous works [19,23,32]. Furthermore, the observed reduction in the modulus of elasticity of the concretes was ascribed to the existence of the glaze and smooth surface of the CWA. It was argued that the glazing surface could weaken the bonding between the cement paste and the aggregate, thereby reducing the elastic moduli of the concretes. The aggregates surface revealed a clean finish and de-bonded appearance after the concrete failure. Besides, some of the CWA were easily pulled out due to bonding failure. Similar observations on CWA based concretes were made in the previous study [10, 17]. The other factor responsible for the modulus of elasticity losses in the proposed concretes may be related to the reuse of the waste aggregates that contained weak material with the low bonding strength on the aggregate surface [33]. Thus, the selection and preparation of the recycled aggregates must consider the surface conditions of the aggregate during the design process of concrete mix.

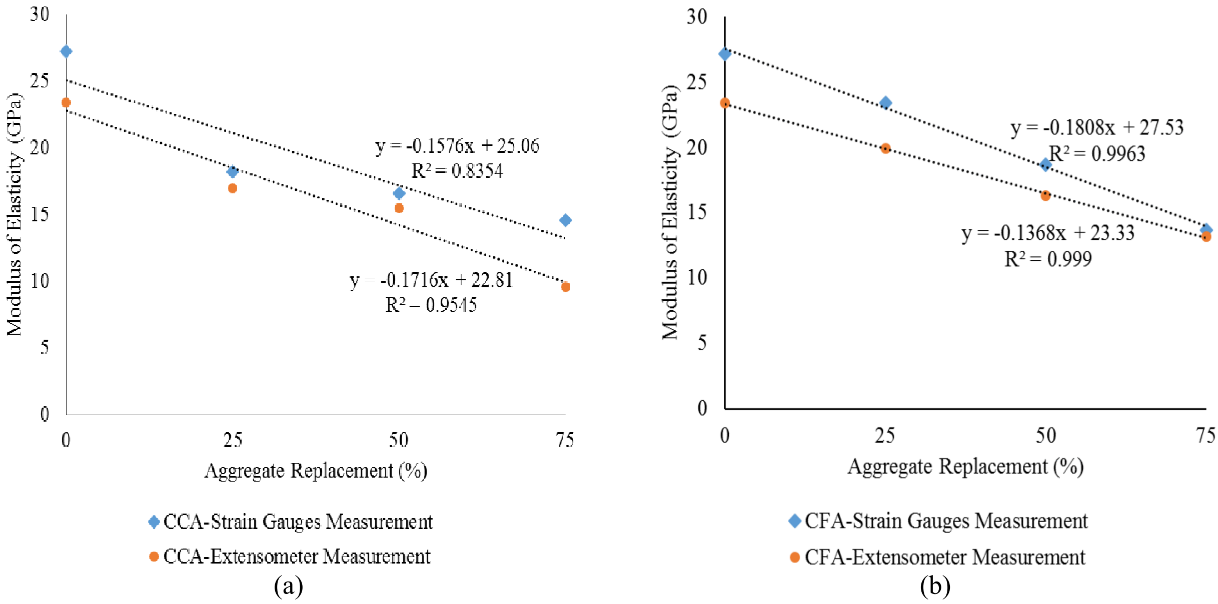

Fig. 3 – The variation in the elastic moduli of the concretes based on (a) CCA and (b) CFA

Figure 4 shows the aggregates replacement percentage dependent to the relative modulus of elasticity of the concretes. The relative modulus of elasticity of the CCA-based concretes was dropped more rapidly than the CFA-based concretes. At 25% of the aggregates replacement, the losses in the modulus of elasticity for the CCA and CFA-based concretes were in the range of 27 to 33% and 14 to 15%, respectively. Furthermore, at 50% of the aggregates replacement, the values of the relative modulus of elasticity were in the range of 34% to 39% and 30% to 31%, respectively. It was also found that at 75% of the aggregates replacement the elasticity of CCA and CFA-based concrete was dropped by 46 to 59% and 44 to 50%, respectively. The variation in the modulus of elasticity losses obtained in the present study was also observed in the other recycled aggregates incorporated concretes made from the construction and demolition wastes [23].

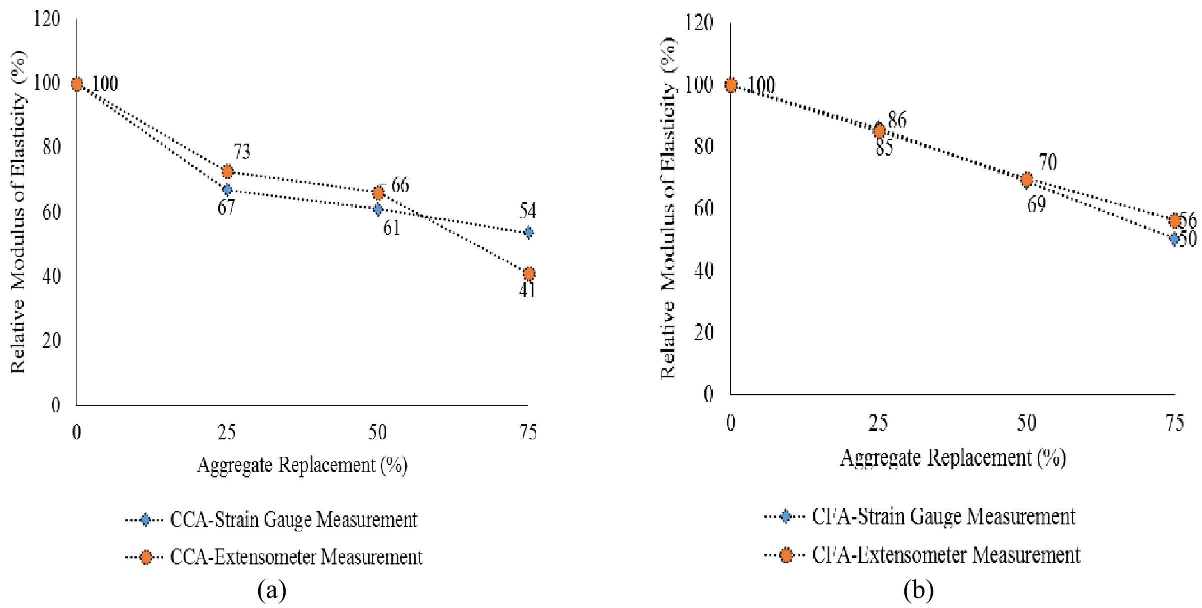

Fig. 4 - The variation in the relative modulus of elasticity of the concretes based on (a) CCA and (b) CFA

It is important to say that the modulus of elasticity is one of the essential mechanical properties of the concrete. The higher the value of the modulus of elasticity, the stiffer is the material. The modulus of elasticity measures the resistance of the material against the elastic deformation under load. According to the Eurocode 2 (EC2), the elastic deformations of the concretes mostly depend on their compositions, especially on the aggregates. Thus, EC2 considered the possibility of producing the concrete using the NA of different geological origin including the basalt, quartzite, limestone, and sandstone. The EC2 also highlighted that the concrete specimens with the same compressive strength but different modulus of elasticity can be obtained using various types of aggregates [23]. Figure 5 compares the modulus of elasticity obtained in the present study with the one suggested by EC2. The modulus of elasticity for the current composition was observed to be similar to that of the limestone and sandstone aggregates. Therefore, the NA used in the present study could have inadequate strength to gain a higher modulus of elasticity in the proposed concretes.

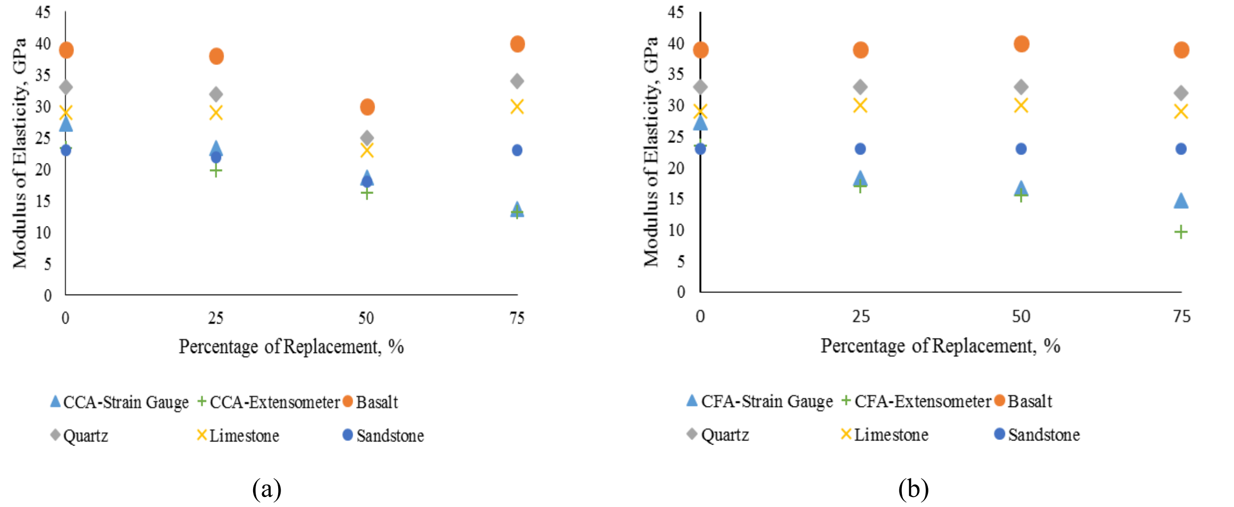

Fig. 5 - Comparison of the modulus of elasticity between Eurocode 2 and CWA-based concretes containing (a) ceramic coarse aggregates and (b) ceramic fine aggregates.

4. Conclusions

The experimental results on the elastic attributes of the CWA-based concretes indicated that the utilization of the CWA in the concrete production is certainly feasible with promising applications in the construction sectors. Based on the findings, the following conclusions can be drawn:

- The CWA properties were shown to be comparable to the NA except for the flakiness and shape of the aggregates. The acceptance of the CWA as substitute for the NA satisfied the desired workability level. The densities of the proposed concretes were decreased with the increase in the CWA contents. The studied CWA-based concretes (both CCA and CFA-based) achieved excellent quality and preferred compressive strength.
- The elastic moduli of the studied concretes were observed to be sensitive on the strain measurement techniques, producing different values.
- The modulus of elasticity was decreased with the increase in the CWA contents, which were due to the surface glaze effect, the quality of the NA and surface properties of the CWA.
- The modulus of elasticity obtained in the present study was found to be slightly lower than the value suggested in the Eurocode 2.
- The proposed green concretes due to their eco-friendliness may be useful for the sustainable development towards the building material industries worldwide.

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