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The Use of Ceramic Tile Waste as Aggregate in Concrete

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Abstract—This paper presents the results of an experimental studyto investigate the potential of using recycled ceramic as aggregate in concrete. The ceramic aggregate used in this study wasrecycled from industrial ceramic tile waste in Egypt. The physical and mechanical characteristics of the recycled ceramic aggregate were investigatedand compared to the conventional aggregates. Eleven concrete mixes with constant w/c ratio were prepared and tested. The reference concrete mix was made withconventional coarse and fine aggregates (crushed stone and natural sand). Five mixes were prepared incorporatingcoarse ceramic aggregate as partial substitute of coarse aggregate with replacement levels of 10%, 20%, 30%, 40%, and 50%. Besides, five mixes incorporated fine crushed ceramic as partial substitute of fine aggregate with replacement levels of 20%, 40%, 60%, 80%, and 100%. Slump test was conducted to investigate the effect of incorporating ceramic aggregates on the workability of fresh concrete. Compressive strength, splitting tensile strength, flexural strength, density, water absorption and sorptivity tests were accomplished to investigate the properties of hardened concrete.The experimental results revealed that the use of recycled ceramic tile aggregates is promising in structural concrete applications.

Index Terms— Coarse ceramic aggregate, Fine ceramic aggregate, Recycled ceramic, Sorptivity

1 Introduction

THE use of recycled materials in concrete manufacture has become more widespread in recent years. The use of recycled ceramic tile waste as aggregate in concrete would contribute to relieve industrial waste disposal problems and would help maintain natural aggregate resources [1].Fengli et al. [2] concluded that it is feasible to reuse recycled ceramic aggregate under 9.5 mm as partial replacement of natural aggregate in concrete. Since the apparent density of ordinary concrete is higher than that of recycled ceramic concrete (RCC), this can be helpful to reduce the self- weight of constructions. Under similar workability condition, when the replacement rate is lower than 20%, the splitting tensile strength of RCC is poor because the ultra-fine sand has high mud content. Moreover, when the replacement rate is greater than 40%, the compressive strength and splitting tensile strength are higher than those of the reference concrete. The use of 100% recycled ceramic as fine aggregate increases both splitting tensile strength and compressive strength significantly [2].

Torgal et al. [3] studied the chemical and physical characteristics of crushed ceramic waste from landfills. Besides, ceramic powder was used in concrete mixes as partial substitution of cement, while fine and coarse ceramic aggregates were used as 100% substitution of fine and coarse natural aggregates. They foundthat compressive strengthincreases by incorporating ceramic waste in concrete.In another study, Al Bakri et al. [4]useddifferent types of recycled ceramic wastes as partial replacement of coarse aggregateinconcrete mixes with different w/c ratio; 0.4, 0.5, and 0.7. It was found that all concrete mixes incorporating ceramic aggregates have compressive strength higher than that of conventional concrete.

Halickaet al. [5] used ceramic sanitary ware waste as coarse aggregate in concrete mixes. Thescanning electron microscopy of the ceramic particles revealed the porosity of their structure. Also, by investigating its properties, it was noticed that ceramic aggregates has low crushing ratio and high water absorption. They reported that high performance concrete as well as high abrasion resistance concrete can be obtained by using ceramic sanitary ware waste aggregate.In another study, Medina et al.[1] used ceramic sanitary ware waste as a partial substitute of gravel with replacement levels 20% and 25%.They found that the incorporation of ceramic aggregate with natural gravel slightly raised the porosity. Both compressive strength and tensile splitting strength increased as replacement percentage increases. In addition, concrete mixes with recycled ceramic aggregate has lower slump, lower density, higher water absorption, higher sorpitivity, and higher porosity compared to that of reference concrete.

On the other hand, de Brito et al. [6]used ceramic wastes from construction and demolition wastes, in concrete mixes as partial replacement of coarse aggregate with replacement ratios of 0, 1/3, 2/3, and 3/3. It was found that as replacement percentages increases, compressive strength, flexural strength, and loss of thickness by abrasion decreased compared to conventional concrete. They reported that since ceramic aggregates have high water absorption, this can be overcome by restoring to pre-saturation procedure.Gonzalez and Etxeberria [7] prepared high performance concrete mixes using mixed recycled aggregate from construction and demolition treatment plant as partial substitution of gravel with replacement levels 20%, 50%, and 100%, in addition to preparing mixes incorporating fine ceramic aggregate as partial replacement of sand with levels 15%, and 30%. They reported that concrete mixeswith fine ceramic aggregate have higher compressive and flexural strengths

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than conventional concrete. While concrete mixes incorporating ceramic mixed aggregates with replacement levels higher than 20% have lower compressive and flexural strengths than conventional concrete.

2 Experimental Work

The experimental work aimed to investigate the potential of using ceramic tile waste as aggregate in concrete. The experimental program was designed to achieve the following objectives:

1) Determining the physical and mechanical characterization of recycled ceramic tile waste aggregate.

2) Studyingthe effect of using recycled ceramic tile waste as partial replacement of fine and coarse aggregateson the properties of both fresh and hardened concrete.

2.1 Materials

The concrete mix constituent materials were: ordinary Portland cement (CEM I 42.5R) complying with EN 197-1[8]provided bythe Arabian CementCompany, natural siliceous sand with fineness modulus 2.68, and crushed stone with particle size of 5-20 mm and a nominal maximum size of 20 mm.A high range water reducing and set retarding concrete admixture “Sikament R 2004” complying with ASTM C 494 Type G [9] was used as a superplasticizer witha constant content (1.5% by weight of cement).

2.1.1 Recycled Ceramic Aggregate

Ceramic tile wastes were crushed into small pieces using a crusher and then sieved to get the required coarse ceramic aggregate particles with sizes ranging from 5 to 20 mm.The fine ceramic aggregate was obtained by sieving the fine crushed ceramic to get particleswith sizesranging from 2.36 mm to 150 µm. Fig. 1 shows the coarse and fine recycled ceramic aggregates used in this study. The characteristics of both conventional and ceramic aggregates were determined according to EN 933[10].

Coarse ceramic aggregate Fine ceramic aggregate

Fig. 1. Recycled ceramic tile waste aggregates

3.1 Mix Proportions

The reference concretemix was designed to meet 30 N/mm2after 28 days using conventional coarse and fine aggregates (crushed stone and sand) withwater to cement ratioW/C= 0.55. Ten concrete mixes incorporating recycled ceramic aggregates were prepared in this study with the sameW/C ratio;five mixes incorporatingcoarse ceramic aggregate as partial substitute of crushed stone with replacement levels of 10%, 20%, 30%, 40%, and 50% and five mixes incorporating fine ceramic aggregate as partial substitute of natural sandwith replacement levels of 20%, 40%, 60%, 80%, and 100%.While concrete mixes in which the fine natural sand was replaced by fine ceramic aggregate was designated as (FCA), the concrete mixes in which the natural crushed stone has been substituted by coarse ceramic aggregate was referred to as (CCA).The mix proportions of the different concrete mixes are given in Table (1).

TABLE 1
Mix Proportions (Kg/m3)

Mix ID	Cement	Crushed Stone	Coarse ceramic aggregate	Sand	Fine ceramic aggregate	Water	Super-plasticizer
Control	387	1075	0	713	0	212	5.8
CCA10	387	960	107	713	0	212	5.8
CCA20	387	840	210	713	0	212	5.8
CCA30	387	724	310	713	0	212	5.8
CCA40	387	611	407	713	0	212	5.8
CCA50	387	502	502	713	0	212	5.8
FCA20	387	1075	0	569	142	212	5.8
FCA40	387	1075	0	420	280	212	5.8
FCA60	387	1075	0	277	415	212	5.8
FCA80	387	1075	0	136	546	212	5.8
FCA100	387	1075	0	0	674	212	5.8

3.2 Test Methods

Slump of the different concrete mixes were determined according to EN 12350-2 [11]. Compressive strength of concrete was determined according to EN 12390-3 [12] using cubic specimenswith dimensions of 100 x 100 x 100 mm. In addition, density of hardened concrete was conducted according to EN 12390-7 [13]. Indirect tension test was conducted according to EN 12390-6 [14] using cylinders of100 mm diameter and 200 mm heightto determine the splitting tensile strength.Flexural strength was determined according to EN 12390-5 [15]using prisms with dimensions of 100 x 100 x 500 mm.The abrasion resistance test was performed according to DIN 52108-07 [16] using cubic specimens of 70x70x70 mm.Percentage of absorption was determined according to ASTM C 642 [17]. Finally, as an indication about durability and permeability, sorptivity test was accomplished according to ASTM C 1585-04 [18].

Three replicates were used for each test and the average value will be used throughout the study.The mechanical properties were determined at 28 days of age except the compressive strength which was determined at 7 days and 28 days.

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4 Results and Discussion

4.1 Properties of Aggregates

The particle size distribution of the used ceramic and conventional coarse and fine aggregates is illustrated in Fig. 2 and Fig.3. It can be seen that the grading of the used coarse and fine ceramicaggregates satisfied the aggregate requirements used for concrete as prescribed by EN 12620:2013 [19].The nominal maximum size for bothcoarse ceramicaggregate and crushed stone is 20 mm.The surfacetexture of the ceramic aggregate particles was found smoother than that of crushed stoneaggregate. The scanning electron microscopy of the used fine ceramic aggregate revealed that the particles had irregular shape, rough surface, and sharp edges. Theglazed partswere represented as white particles as shown in Fig. 4.

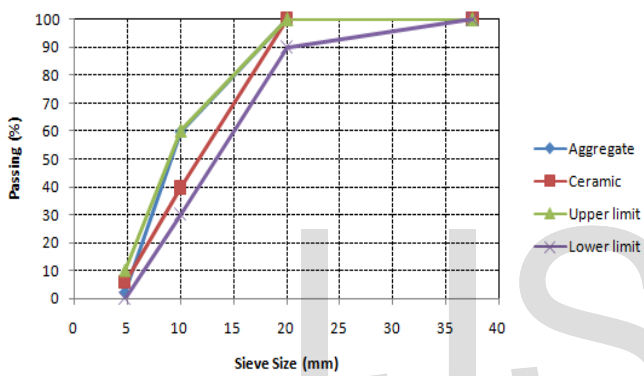

Fig. 2. Particle size distribution of coarse aggregates

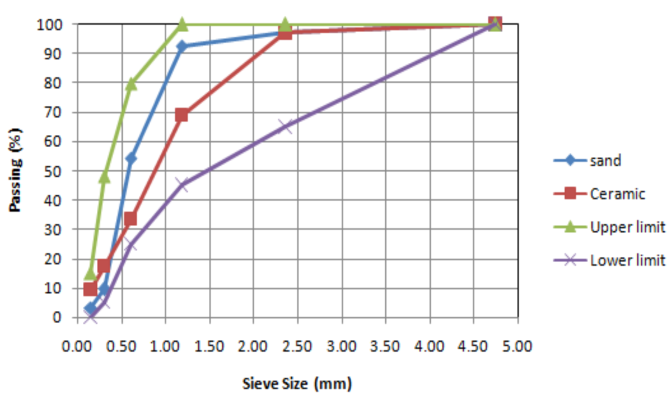

Fig. 3. Particle size distribution of fine aggregates

The apparent specific gravity for both fine and coarse ceramic aggregate was found to be2.49 and 2.33, respectively, whereas it was 2.66 and 2.68 for natural fine and coarse aggregate, respectively. The waterabsorption for ceramic waste ranged from 5.10 % for fine ceramic aggregate to 5.50 % for

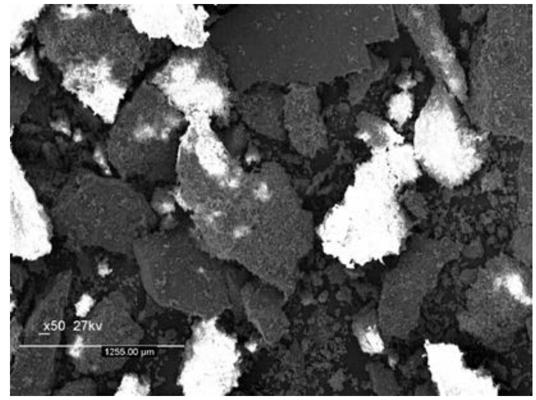

Fig. 4. SEM of the used fine ceramic tile waste aggregate (50 x)

coarse ceramic aggregatewhereas for crushed stone ranged from 1.02 % for fine aggregate to 1.80 % for coarse aggregate.The bulk density of ceramic aggregates was generally found to be a little bit lower than that of natural aggregates. The different measured physical and mechanical properties of aggregates are summarized in Table (2).

Table (2) shows that the physical and mechanical properties of ceramic aggregates are to some extent close to those of the natural aggregates except for water absorption andclay lumps and friable particles. Water absorption of ceramic aggregates was considerably higher than natural aggregates.

TABLE 2
Mechanical and Physical Properties of Used Aggregates

Property	Coarse Aggregate		Fine Aggregate	
	Crushed Stone	Ceramic	Sand	Ceramic
Bulk specific gravity	2.557	2.066	-	-
Apparent specific gravity	2.680	2.331	2.667	2.494
Water absorption (%)	1.8	5.5	1.02	5.1
Bulk density (Kg/m^3)	1494	1330	1630	1204
Voids (%)	41.43	35.48	-	-
Los Angles Coefficient (%)	22.20	27.10	-	-
Elongation Index (%)	2.04	10.39	-	-
Flakiness Index (%)	1.36	14.11	-	-
Clay lumps and friable particles (%)	-	-	2.2	6.0
Fineness Modulus	6.37	6.55	2.44	2.74

The properties of coarse and fine ceramic aggregates were found to comply with specification limits except for water absorption of ceramic coarse and fine aggregates and clay lumps of fine ceramic aggregates. Both water absorption and clay lumps are higher than that prescribed by EN 12620:2013 [19].

4.2 Properties of Concrete Incorporating Ceramic Waste Aggregates

4.2.1 Slump of Concrete Mixes

The use of coarse or fine ceramic aggregate as replacement of crushed stone or sand in concrete mixes resulted in a decrease in the slump as the percentage of the replacement ratio increases as shown in Fig. 5 and Fig. 6. When replacement of coarse aggregates reached 50%, the loss in slump was 61.1%, while loss in slump reached 100% when replacement level of fine aggregate was 60%. This expected reduction of slump is due to the high water absorption of ceramic aggregates.

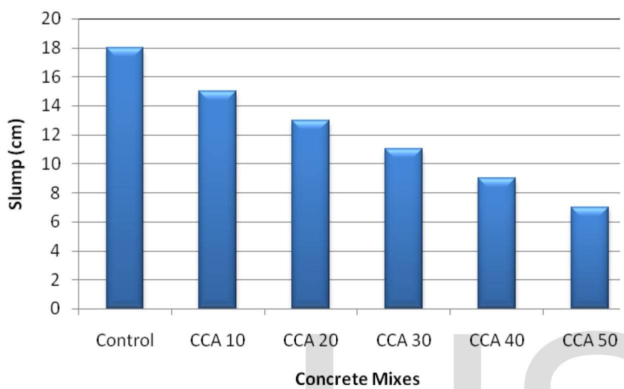

Fig. 5. Slump of concrete mixes with coarse ceramic aggregate

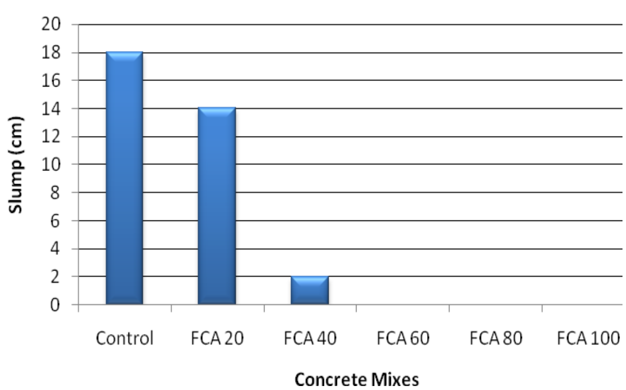

Fig. 6. Slump of concrete mixes with fine ceramic aggregate

As mentioned before, the control concrete mix was designed to obtain a target mean compressive strength after 28 days equal to 30 N/mm2. The compressive strength results at 7-days and 28-days of concrete mixes incorporatingcoarse ceramic aggregate with replacement levels equal to 10%, 20%, 30%, 40% and 50% are shown in Fig. 7. The figure shows fluctuation in compressive strength when coarse ceramic aggregate was used with different replacement levels. This fluctuation could be attributed to the fact that most types of ceramic tiles have glaze on its surface and consequently be smoother than the other surface. The surface with glaze leads to a lower cohesion between the crushed ceramic tiles utilized as aggregate and the cement paste. On the other hand, the high water absorption of ceramic aggregate leads to decrease in free-water and hence to an increase in strength. Therefore, the dual effect of these both facts may lead to an increase or adecrease or in other word afluctuation in flexural strength depending on the glaze content.

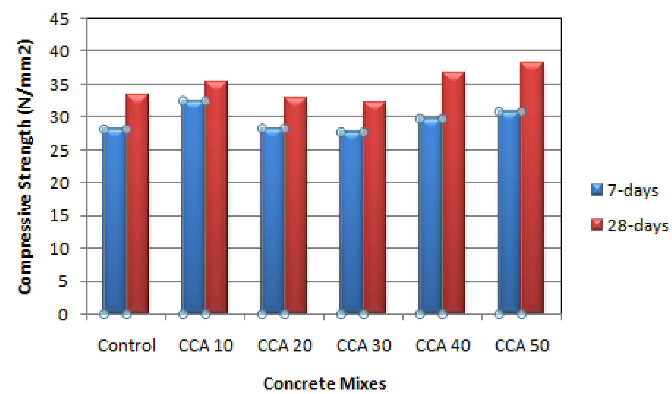

Fig. 7. Compressive strength of concrete mixes with coarse ceramic aggregate

Fig. 8 shows the compressive strength results at 7-days and 28-days of concrete mixes incorporating fine ceramic aggregates with replacement levels equal to 20%, 40%, 60%, 80% and 100%. It was found that the compressive strength at 7-days and 28-days increases significantly as the replacement level of fine ceramic aggregate increases. This could be attributed to the high water absorption of ceramic aggregates that leads to a decrease of free water content and consequently the compressive strength increases. Here the effect of glaze is very weak since the particles are smaller in size and so most of glaze was crushed to fines and may act as microfibers which in turn might enhance the concrete pore structure.

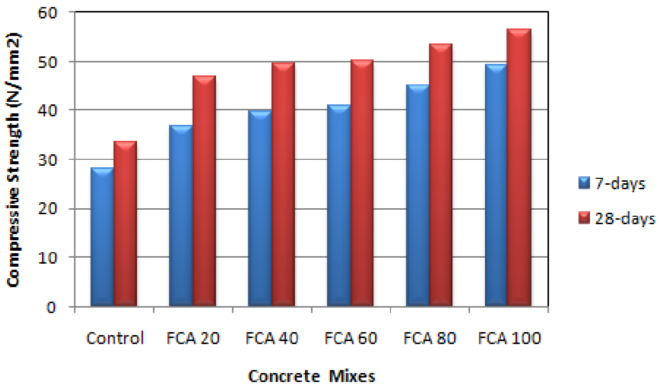

Fig. 8. Compressive strength of concrete mixes with fine ceramic aggregate

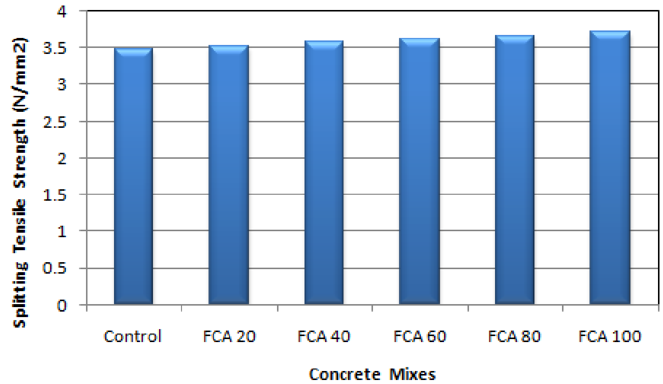

Fig. 10. Splitting tensile strength of concrete mixes with fine ceramic aggregate

4.2.3 Splitting Tensile Strength

The splitting tensile test results at 28-days are shown in Fig. 9 and Fig.10. It was found that the use of coarse ceramic aggregate in concrete mixes with replacement levels of 10%, 20%, 30%, 40%, and 50%, slightly decreased the splitting tensile strength of concrete compared to that of control mix. The variations in the obtained results may be justified by the presence of glaze particles attached to the ceramic aggregates which causes a decrease in cohesionbetween ceramic aggregate and cement paste decreasesleading finally to a decrease in the tensile strength. This means that theglaze negative effect on strength overcame the increase in strength due to the reduction in free water content associated with using ceramic aggregate, as stated before.

Upon using fine ceramic aggregates in concrete mixes with replacement levels of 20%, 40%, 60%, 80%, and 100%, the splitting tensile strength was found to increase slightly as replacement level increases. This increase may be due to the decrease in free-water content since ceramic aggregates have high water absorption.

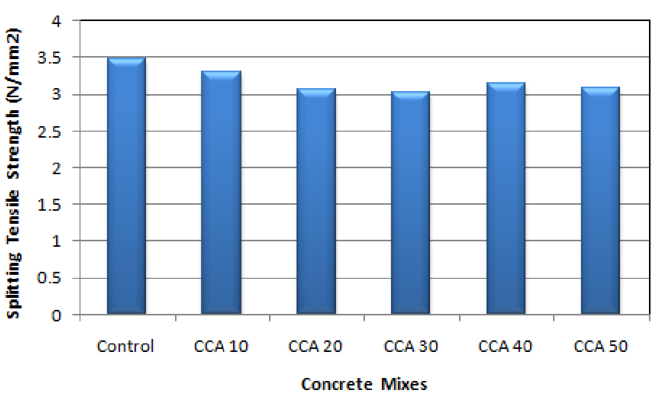

Fig. 9. Splitting tensile strength of concrete mixes with coarse ceramic aggregate

4.2.4 Flexural Strength

The flexural strength results at 28-days are illustrated in Fig. 11, and Fig. 12. The results show that the flexural strength of concrete mixes incorporating coarse ceramic aggregate slightly less than that of control mix depending on the amount of glaze attached to ceramic aggregate. While, flexural strength of concrete mixes incorporating fine ceramic aggregate increases as replacement level increases.This increase of flexural strength may be due to the decrease in free wateras well as the expected enhancement of pore structure in concrete mixes as the very fine ceramic sand may act as fibers.

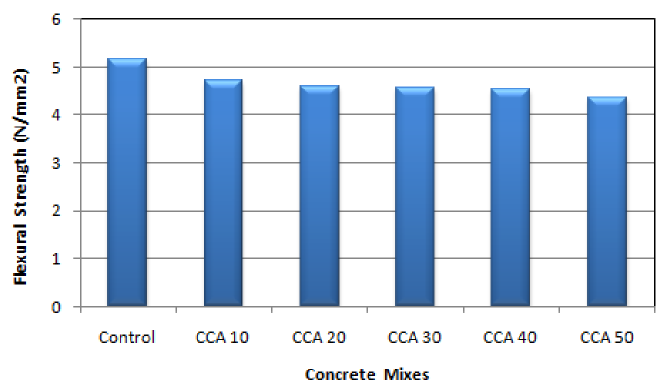

Fig. 11. Flexural strength of concrete mixes with coarse ceramic aggregate

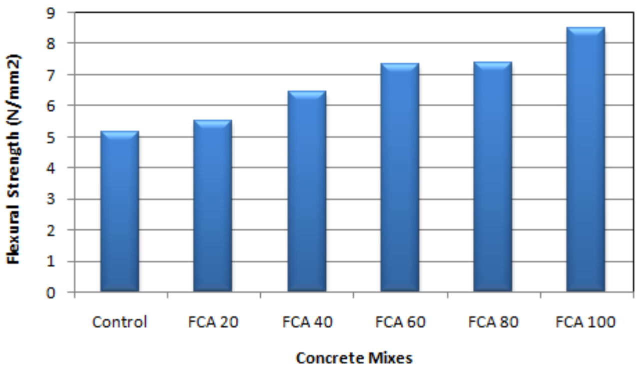

Fig. 12. Flexural strength of concrete mixes with fine ceramic aggregate

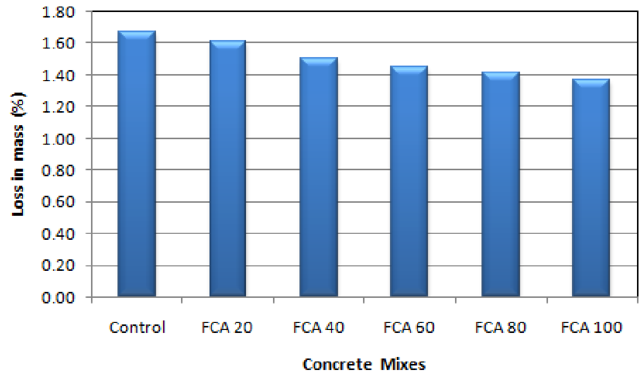

Fig. 14. Loss in mass of concrete mixes with fine ceramic aggregate

4.2.5 Abrasion Resistance

Results of abrasion test for different concrete mixes are represented Fig. 13 and Fig. 14. It was found that although Los Angeles test results showed that the used crushed stone has higher abrasion coefficient than ceramic aggregate, the incorporation ofcoarse ceramic aggregate in concreteenhanced slightly its abrasion resistance which appeared in the reduction in the percentage of loss in mass after 28 days. Moreover, this descending trend of the percentage of loss in mass has been interrupted at certain replacement ratios, as illustrated in Fig. 13.

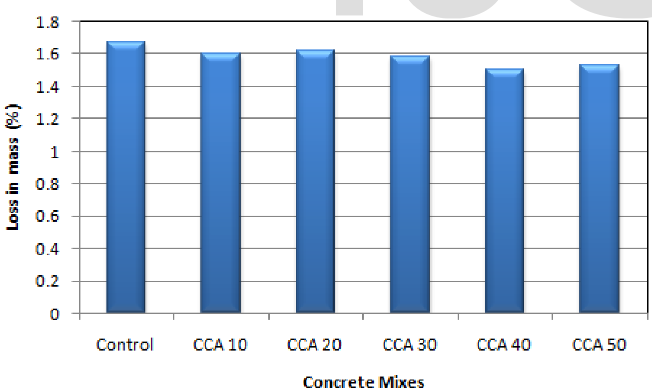

Fig. 13. Loss in mass of concrete mixes with coarse ceramic aggregate

The general slight enhancement of concrete abrasion resistance could be comprehended by taking into consideration the high water absorption of ceramic aggregate leading to a decrease in free-water content and consequently to an enhancement in the microstructure of the concrete mixes in addition to the existence of glaze particles, with very high abrasion resistance, in coarse ceramic aggregate. On the side, the fluctuation in the loss of mass could be interpreted based on the fact that the crushed ceramic tile aggregate containsdifferent amounts of glaze particles distributed inthe specimen layers. Therefore the test results may be affected by the place of taking or cutting the specimen.

It can be seen that on using crushed fine ceramic aggregate in concrete mixes, the loss in mass of concrete specimens decreases as the replacement ratio increases.All ceramic mixes show better results compared to the control mix. This may be due to the filling effect of pore structure and enhancement of microstructure resulted from high water absorption of ceramic aggregate that leads to decrease in free-wateras replacement ratio increases.

4.2.6 Density and Percentage of Absorption

Results of density of hardened concrete after 28 days in saturated conditions for different concrete mixes are listed in Table (3).Test results show that density of concrete with ceramic aggregates decreases slightly compared with the control mix as replacement ratio increases. This is due to that ceramic aggregates have less density than the used natural aggregates.

TABLE 3
Water Absorption, and Density in Concrete Mixes with Ceramic Aggregate

Mix ID	Density of hardened concrete (kg/ m3)	Absorption after immersion (%)	Absorption after boiling (%)
Control	2425	8.64	8.82
CCA10	2390	7.80	8.16
CCA20	2297	7.43	8.17
CCA30	2303	7.57	8.59
CCA40	2315	7.66	8.64
CCA50	2342	8.00	8.38
FCA20	2396	7.21	7.52
FCA40	2357	7.05	7.24
FCA60	2378	6.46	6.82
FCA80	2362	6.22	6.47
FCA100	2287	6.08	6.26

Regarding water absorption, test results of CCA in comparison with the control concrete mix showed no remarkable differences or a detectable trend in spite of that water absorption of coarse ceramic aggregate was significantly higher than that of the natural coarse aggregate, as mentioned before. This might be clarified through that the coarse ceramic aggregate has most probably reached its saturation condition from the mixing water leading finally to the undetected change in concrete water absorption from CCA to the control one.

On the other hand, test results of FCA have reflected relatively a clear reduction in water absorption in comparison with the control mix. This experimental finding could be justified considering that fine ceramic could have reached its saturation state from the mixing water, similar to coarse ceramic aggregate, in addition to that fine ceramic aggregate has a filling effect which in turn enhanced the concrete pore microstructure leading finally to a decrease in the water absorption.

4.2.7 Capillary Water Absorption (Sorptivity)

The initial rate of absorption (capillary absorption coefficient) is the slope of the absorption per unit area versus the square root of time in the first six hours. While, the secondary rate of absorption is the slope of the absorption per unit area verses square root time in the following seven days. The results of the initial rate of absorption and secondary rate of absorption of different concrete mixes at the age of 28 days are shown in Fig. 15 and Fig. 16.

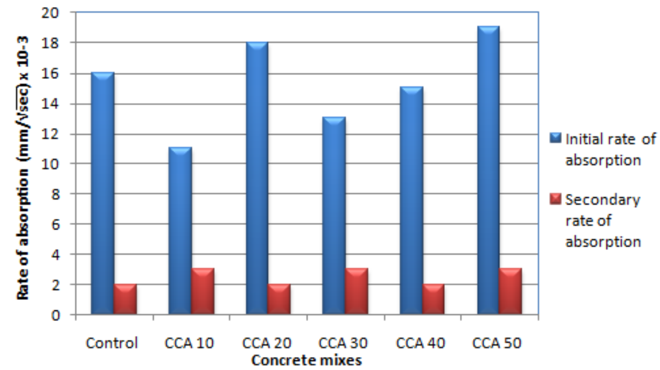

Fig. 15. Initial and secondary rate of absorption of CCA

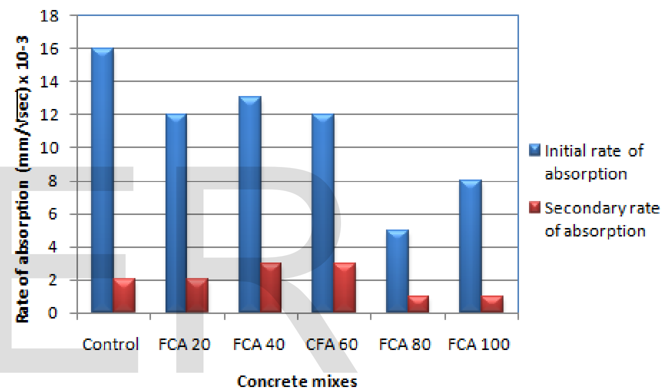

Fig. 16. Initial and secondary rate of absorptionof FCA

The initial and secondary rates of absorption of the referenceconcrete were 0.016 mm/sec0.5 and 0.002 mm/sec0.5 respectively. Test results of different concrete mixes showed a little bit variations compared to the control mix. For concrete mixes incorporated coarse ceramic aggregate, no clear trend or a remarkable variation in rate of absorption variation could have been detected which is owed to the existence or absence of the glazed particles in the sections subjected to water. When section subjected to has glazed particles, the sorptivity decreases and when the cutting section is free of glazed particles, the rate of absorption increases.

On the other hand, the initial and secondary rates of absorption of concrete mixes incorporatingfine ceramic aggregate was generally lower than those of the control mix. This enhancement in the fine ceramic concrete mixes may be due to filling effect of the fine ceramic aggregate that improve the concrete pore structure.

5 Conclusion

The present research focused on investigating the mechanical and physical properties of the recycled ceramic tile aggregate and the different characteristics of concrete incorporating this type of aggregate compared with concrete made of natural aggregate. Based on the results of the experimental work carried out in this research, the following conclusions could be drawn.

First, the use of ceramic aggregates enhances some of the concrete properties such as compressive strength due to decrease in free-water. On the other hand, a decrease in workability was detected as the percentage of replacement increases since ceramic has high water absorption. Therefore, slump decreases as percentage of ceramic waste replacement increases for all cases. The decrease was remarkable in case of fine ceramic aggregate.

Second, for sand replacement, compressive strength increases as the replacement level increases. The compressive strength ratio ranges from 130% to 170% of that of the control mix. Hence, no significant difference was detected in tensile strength in case of replacing both coarse ceramic aggregates and fine ceramic aggregates.

Moreover, flexural strength ratio for coarse ceramic aggregate replacement ranges from 85% to 91% of that of the control mix. While, flexural strength ratio for fine ceramic aggregate replacement ranges from 106% to 165% of that of the control mix.

In addition, abrasion resistance of concrete slightly differs from the control mix. It was noticed that all mixes have better abrasion resistance than the control concrete mix. While, no remarkable difference was found in water absorption by replacement of coarse aggregate. The water absorption with fine aggregate replacement decreased by 30% compared to that of the control mix.

Also, concrete mixes with coarse ceramic aggregate have nearly the same initial and secondary rate of absorption as the control mix, while the initial and the secondary rate decrease with the replacement of the fine ceramic aggregate.

Finally, It is feasible to use coarse ceramic aggregate as partial replacement of crushed stone up to 50% and fine ceramic aggregate as a partial replacement of natural sand up to 40%.

It is promising to use ceramic aggregate in structure concrete provided that more researches have to be performed to investigate some other characteristics of concrete with recycled ceramic aggregate such as long term durability, fire resistance, and corrosion of steel imbedded in such concrete.

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