EFFECT OF RECYCLED CONCRETE AGGREGATE QUALITY ON PROPERTIES OF CONCRETE

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ABSTRACT

The possibility of the use of recycled aggregates from the construction industry in green concrete production is of increasing importance to reduce the negative environmental impact associated with construction and demolition wastes. The objective of this study is to investigate the effect of recycled concrete aggregate (RCA) quality on the properties of hardened concrete properties such as compressive strength, splitting tensile strength, density, water absorption capacity and porosity accessible to water. The RCA used in this study was obtained from the crushing of waste concrete with two different compressive strengths (LRCA obtained from the crushing of waste concrete having compressive strengths below 30 MPa and HRCA obtained from the crushing of waste concrete having compressive strengths above 30 MPa). The natural coarse limestone aggregate was 100% replaced with coarse LRCA and HRCA. As a result of the study, the use of 100% HRCA and %100 LRCA instead of limestone coarse aggregate in the concrete adversely affected its mechanical and physical properties. In addition, HRCA showed better performance in terms of compressive strength, tensile strength, water absorption and porosity compared to the use of LRCA. Furthermore, the percentage of adhered mortar on the surface of LRCA and HRCA was analyzed using a computerized micro tomography device, and it was found that the percentages of attached mortar and aggregates are 61% and 35.5% for LRCA, whilst the attached mortar and aggregate contents for HRCA are 45.9% and 53.7%, respectively.

KEYWORDS

X-Ray computed micro tomography, recycled concrete aggregate, adhered mortar

1. INTRODUCTION

World population growth and the accelerating urbanization in the major cities of developing countries is causing a depletion of natural resources and the generation of excess waste materials. With the acceleration of an Urban Renewal Program in large cities of Turkey, finding landfills for construction wastes has become a challenge. Due to these large scale demolitions, large amounts of wastes are produced causing serious environmental pollution, including a disposal

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problem. In addition, it has been reported that approximately 900 million tons of construction and demolitions wastes are produced annually in the European Union and represents around 25–30% of total waste generated (Bravo et al., 2015; Sadati et al., 2016; Yap et al., 2018). Furthermore, more than 3 billion tons of construction and demolition wastes were generated in 2016 by 40 countries worldwide (Akhtar and Sarmah, 2018; Hu et al., 2019). Therefore, there is an impetus for special measures to deal with the wastes generated by the construction industry. The possibility, then, of using recycled aggregates from the construction industry in concrete production is of increasing importance to reduce the negative environmental impact associated with construction waste.

Due to the ingredients of a concrete mixture (cement, coarse and fine aggregate, water and admixtures) aggregate taking about 70% of concrete's volume, it can be seen that the concrete industry consumes a huge amount of natural aggregate and creates severe environmental problems. For this reason, the use of recycled aggregates in concrete production may reduce the depletion and the scarcity of natural aggregate reserves, while also reducing the disposal problem of concrete wastes.

Recycled concrete aggregate (RCA) obtained by crushing concrete wastes from construction and demolition wastes (CDW) has recently attracted special interest in civil engineering. The utilization of CDW in the production of concrete, especially concrete waste as aggregate, reduces the environmental damage of natural aggregate reserves consumption and their environmental impact, as well as minimizes the damage of these wastes to the environment (Çakır, 2014; McGinnis et al., 2017; Thomas et al., 2018). The major disadvantage of the RCA is the weak mortar layer adhered on its surface. The weak mortar layer detracts from many of the RCA properties, including its water absorption capacity; thus, there are limits to the use of RCA and its inclusion level in concrete mixtures (Tegguer, 2012; Yang and Lim, 2018). In addition, the presence of more than one interfacial transition zone (ITZ) between aggregates and cement paste in recycled concrete aggregate, which is the weakest phase in concrete, is the most important weakness of RCA compared to natural aggregate. Further, the mechanical properties of concrete produced with RCA is related to the water/cement ratio, the cement amount, the aggregate quality, porosity as well as the aggregate-matrix interface bond of the original concrete (Yehia et al., 2015).

Compared to natural aggregate, RCA is a composite material composed by natural aggregate and old cement mortar. The weak and porous structure of the attached mortar on the surface of RCA is responsible for its high water absorption capacity (Verian et al., 2018; Kurda et al., 2019), the high Los Angeles wear loss (Pedro et al., 2017; Omary et al., 2016, Soares et al., 2014; Younis et al, 2013) and the low density (Beltran et al., 2014; Gesoğlu et al., 2015; Kapoor et al., 2016) compared to natural aggregate. One of the critical parameters affecting the use of RCA is the variability of aggregate properties. Therefore, the quality of RCA depends on the quality of the parent concrete (Yehia et al., 2015; Assaad and Daou, 2017; Zou and Chen, 2017).

Many researchers have stated that the magnitude of the decrease in strength of the concrete containing RCA is dependent on the type and compressive strength of the original concrete, the replacement rate, the water/cement ratio and the moisture content of the aggregate (Dimitriou et al., 2018). It is possible to better understand the strength of the RCA by using recycled aggregates of different quality. Experimental studies show that concrete containing RCA is clearly more permeable than concrete containing natural aggregate. However, as the durability of concrete is dependent on permeability, it is possible to enhance the concrete durability with supplementary, cementitious materials such as fly ash, silica fume, and granulated blast furnace slag (Omrane et al., 2017; Dimitriou et al., 2018).

The effect of RCA quality on the properties of fresh and hardened concrete has been documented in many previous studies (Kou and Poon, 2015; Etxeberria et al., 2002; Rao et al., 2007, Koper et al., 2016). Generally, compared to natural aggregate, the use of RCA in concrete increases the drying shrinkage, creep, water absorption by immersion, water absorption by capillary action, water permeability, carbonation rate and chloride ion ingress rate. However, the compressive strength, tensile strength, abrasion resistance, modulus of elasticity, frost resistance and sulfate resistance are believed to be lower for concrete containing RCA compared to concrete with natural aggregate. The lower performance of RCA is generally related to the weak and porous structure of the mortar adhered on the surface of the original natural aggregate. For that reason, different methods for the determination of the amount of mortar attached on the surface of RCA for quality control purpose have been reported by various researchers (Abbas et al., 2007; Abbas et al., 2006; Juan and Gutierrez, 2004; Nagataki et al., 2000; Ravindrarajah and Tam, 1985). However, those methods such as heat treatment are energy consuming and may no longer be sustainable. Hydrochloric acid can also dissolve some aggregate types such as limestone. Therefore, a non-destructive method was proposed in this present study to characterize recycled aggregate, specifically the amount of mortar attached in the original natural aggregate.

In this study, the effect of RCA quality on the properties of fresh and hardened concrete properties such as compressive strength, splitting tensile strength, density, water absorption capacity and porosity accessible to water was investigated. Furthermore, based on the fact that the adhered mortar alters more properties of RCA and limits its utilization in concrete, the percentage of attached mortar on the surface of RCA was evaluated by X-Ray computed micro tomography technique.

2. EXPERIMENTAL STUDY

2.1 Materials

In this study, an ordinary Portland cement CEM I 42.5R type cement conforming to EN 197-1 standard with a specific gravity of 3.15 and a Blaine specific surface of 3677 cm^2/g was used as a binder. The chemical composition and some physical and mechanical properties of Portland cement obtained from its manufacturer are given in Table 1.

Aggregates used in the concrete mixes production were obtained from three different origins. The first of these aggregates is crushed coarse limestone and fine aggregate. The second and third types of aggregate were obtained from the crushing of concrete with two different compressive strength levels. The recycled concrete aggregates to be used instead of limestone coarse aggregate were obtained from the crushing of concrete waste with a low and high compressive strength (below 30 MPa and above 30 MPa). High strength concrete used to produce RCA was produced in laboratory while low strength concrete was supplied from the demolition of an old building and brought to the laboratory. The collected concrete wastes were first divided into small pieces by the help of sledge hammers, and then they were brought to the size of aggregate with the help of a laboratory type jaw crusher. Aggregates coming out of the crusher were sieved from 25 mm, 15 mm and 5 mm sieves, and were stored to be used in the production of concrete mixes. The crushed recycled aggregates were also remixed in order to fulfill the same gradation with limestone aggregate. The sieve analysis results as well as the grading curves with respect to TS 802 limitations are presented in Figure 1. LRCA and HRCA denote the RCA

TABLE 1. Chemical, physical and mechanical properties of cement.

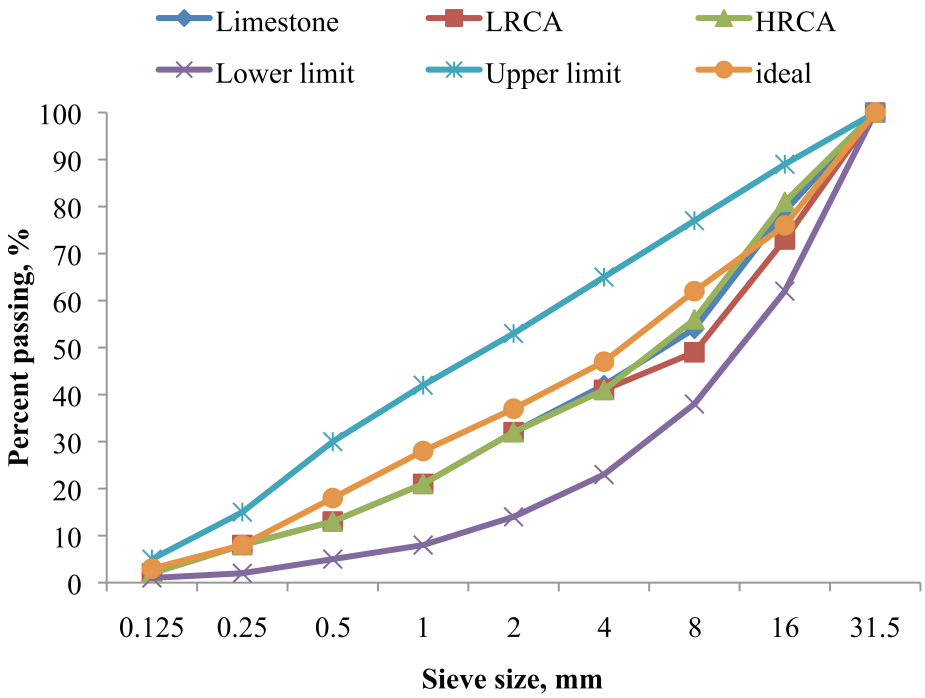
Chemical composition (%)	
SiO_2	19.52
Al_2O_3	5.39
Fe_2O_3	2.48
CaO	62.5
MgO	1.09
Na_2O	0.27
K_2O	0.8
SO_3	3.41
Loss on ignition (LOI)	1.42
Cl^-	0.0074
Insoluble residue (IR)	0.63
Free CaO	1.06
Physical properties	
Specific gravity	3.1
Specific surface area (cm^2/g)	3677
Initial setting time, (min)	150
Final setting time, (min)	200
Compressive strength (MPa)	
3-day	30.8
7-day	39.3
14-day	45.4
28-day	49.6

obtained from the crushing of waste concrete having compressive strength below 30 MPa and waste concrete having compressive strength above 30 MPa, respectively.

The surfaces of coarse recycled aggregate were also analyzed using an optical microscope and the surface views are presented in Figure 2. As seen in Figure 2, RCA obtained from the crushing of waste concrete having compressive strength below 30 MPa (LRCA) has more attached mortar on its surface compared to RCA obtained from the crushing of waste concrete having compressive strength above 30 MPa (HRCA).

Polycarboxylic ether-based high range water reducing (HRWR), as workability agent, was added to the fresh concrete mixture where it was needed to achieve the required flow. The used chemical admixture conforms to ASTM C 494 type F and can be used up to 1.5% of cement

FIGURE 1. Tested limestone, HRCA and LRCA particle's grading with respect to TS 802 limitations.



weight. Some technical properties of the used superplasticizer given by its manufacturer are shown in Table 2. The flow values of the fresh concrete were determined in accordance with ASTM C 1437-15 and the recorded flow values were in the range of 150 ± 20 mm.

2.2 Concrete composition and curing

In this study, three concrete mixes were designed. In addition to the control mix (RC) containing limestone aggregate, two different mixes containing RCA, one with 100% replacement ratio of coarse limestone by LRCA (LRC) and another with 100% replacement ratio of coarse

FIGURE 2. Microscopic images of LRCA (left), HRCA (right).

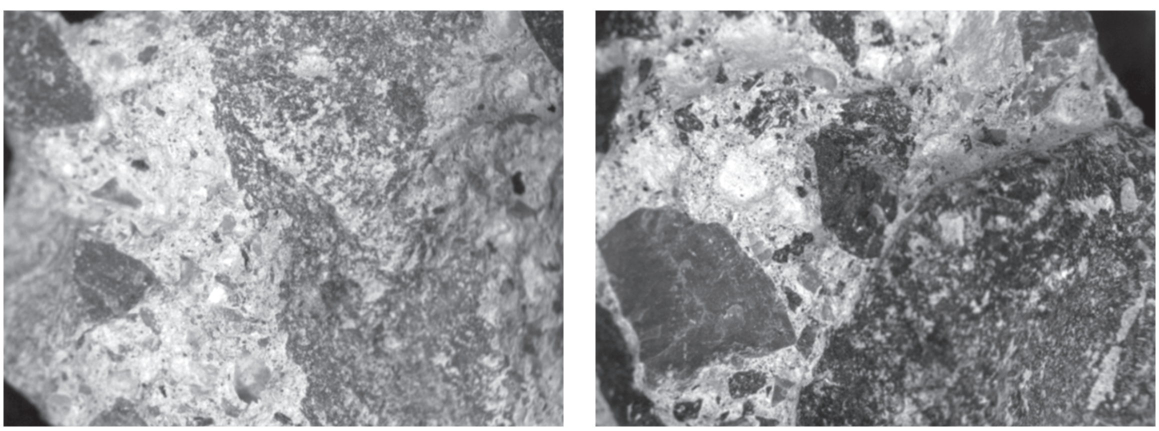


TABLE 2. Technical properties of used admixture.

Technical properties	
Structure of the material	**Polycarboxylic Ether-based**
Color	Amber
Density	1.069–1.109
pH	5–7
Alkaline content (%)	≤3
Chlorine content (%)	≤0.10
Application ratio (%)	0.8–1.5

limestone by HRCA (HRC) were produced. Due to the lower specific gravity of RCA compared to that of limestone aggregate, the replacement of the aggregates was made in terms of volume. The water/cement ratio was kept constant at 0.5 while the coarse aggregate/total aggregate ratio was 0.58. The composition of the concrete mixes is given in Table 3. The target slump was 150 ± 20 mm. Due to the higher water absorption capacity of RCA compared to natural aggregate, for mixes containing RCA, extra water equivalent to the water absorption capacity of the RCA was added during the mixing process to avoid the decrease of required mixing water as suggested by many researchers (Abreu et al., 2018; Ferreira et al. 2011; Fonseca et al., 2011).

The concretes were mixed in a drum type mixer of 40 dm^3 capacity. For the RC mix, aggregates and cement were dry-mixed for 2 minutes. Thereafter, mixing water and superplasticizer were added to the dry mix and mixing was resumed until a homogenous mixture was achieved. For HRC and LRC mixes, first, aggregates with an extra amount of water equivalent to the absorption ratio of the RCA were mixed for 2 minutes and then set aside for 30 minutes before adding the other ingredients. The fine aggregate and cement were then added to the mix. Thereafter, mixing water and plasticizer were added and mixed until achieving a homogenous mixture. The samples were demolded one day after casting and cured in water at approximately

TABLE 3. Composition of the concrete mixes.

Components (kg/m^3)	**RC**	**HRC**	**LRC**
Cement	404	404	404
Water	202	202	202
Fine limestone aggregate	813	813	813
Coarse Limestone Aggregate	1108	0	0
Coarse RCA	0	947	856
Superplasticizer	2.0	2.7	2.5
Fresh unit weight (kg/m^3)	2325	2155	2068

20°C for 28 days. The specimens used were 100 x 200 mm cylinders for splitting tensile strength and 100 mm cubes for both compressive strength and water absorption.

2.3 Tests

Limestone and RCA aggregates were tests for grading (ASTM C136/C136M-14), bulk density (ASTM C29/C29M-17a), water absorption (ASTM C127-15 and ASTM C128-15), Los Angeles wear (ASTM C535-16) and flakiness index (TS EN 933-3). Slump test (TS EN 12350-2) and fresh state density (TS EN 12350-6) were performed on fresh state concrete whereas the hardened state tests including density (TS EN 12390-7) compressive strength at 7 and 28 days (TS EN 12390-3), splitting tensile strength at 7 and 28 days (TS EN 12390-6), water absorption and porosity (ASTM C 642-13) at 28 days were performed on hardened concrete.

3. RESULTS AND DISCUSSIONS

3.1 Physical properties of aggregates

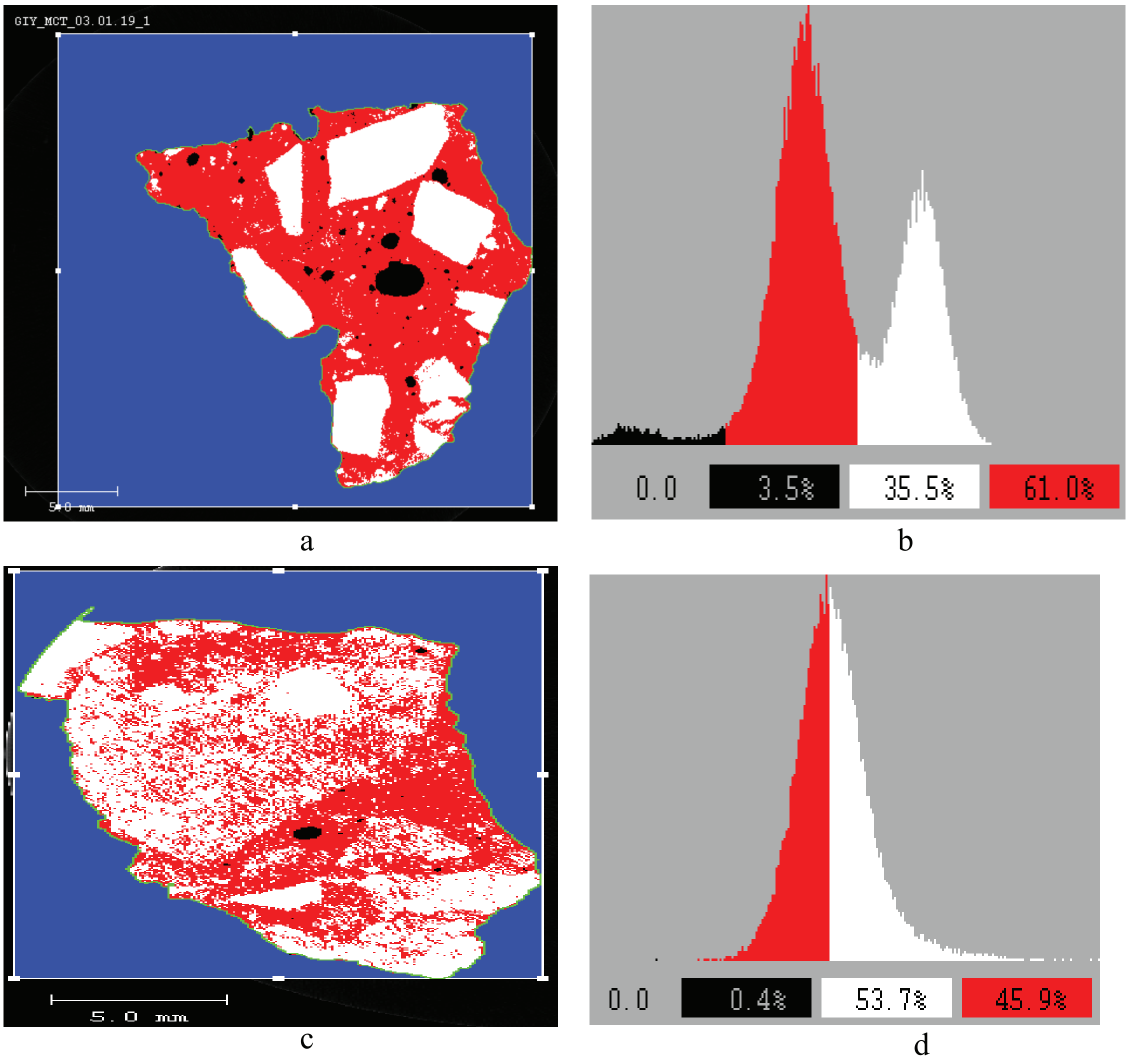
Some physical properties of limestone and recycled coarse aggregates are given in Table 4.

As seen from Table 4, LRCA and HRCA exhibit lower density and higher water absorption than limestone aggregate. However, HRCA has a higher quality than LRCA. The inferior quality of recycled aggregates may be due to the weak mortar layer adhered on their surface. This weak mortar layer detracts from many properties of the RCA, including its water absorption capacity; thus it can limit the use of RCA or lowers its inclusion level in concrete mixtures. The adhered mortar content, the aggregate fraction content as well as the porosity of the RCA was evaluated with X-Ray computed micro tomography and the results are presented in Figure 3. As seen from Figure 3, the attached mortar and aggregates content are 61% and 35.5% for LRCA whilst the attached mortar and aggregate contents for HRCA are 45.9% and 53.7%, respectively. The

TABLE 4. Properties of limestone aggregate, LRCA and HRCA.

Properties	Limestone aggregate			LRCA		HRCA	
	0–5 mm	5–15 mm	15–25 mm	5–15 mm	15–25 mm	5–15 mm	15–25 mm
Bulk density, (kg/m^3)							
Compacted	1889	1573	1548	1194	1128	1334	1274
Loose	1673	1480	1466	1076	1052	1215	1196
Specific gravity							
Dry	2.632	2.654	2.693	2.043	2.092	2.263	2.312
Saturated surface dry	2.656	2.676	2.711	2.218	2.266	2.387	2.432
Water absorption (%)	0.92	0.3	0.23	8.57	8.32	5.47	5.21
Los Angeles coefficient (LA)	25.6			40.52		27.04	
Flakiness index (%)	20.15			16.23		29.3	

FIGURE 3. Percentage of aggregates, mortars and porosities in LRCA (a and b) and HRCA (c and d) obtained by X-Ray computed micro tomography.



porosity of LRCA and HRCA was also evaluated as 3.5% and 0.4%, respectively. White, red and black colors denote aggregate, mortar and porosity of RCA.

The Los Angeles (LA) abrasion test results showed that LRCA was less resistant to fragmentation as seen from Table 4 compared to limestone and HRCA aggregate.

3.2 Fresh concrete results

The results of the slump and fresh state unit weight values of the concrete mixes are given in Table 5. As seen from Table 5, the replacement of coarse limestone aggregate with coarse RCA causes a decrease in the slump value. This decrease may be due to the angular and roughened surface texture of RCA that increases internal friction in fresh concrete. The fresh unit weight of the concrete mixes decreased up to 7.3% and 11% when coarse limestone aggregate was replaced with coarse HRCA and LRCA, respectively. The decrease of the unit weight is expected as the unit weight of the fresh concrete depends directly on the specific weight of its ingredients and the specific gravity of HRCA and LRCA are lower than that of limestone aggregate.

TABLE 5. Slump and fresh state unit weight results.

Concrete code	Slump (mm)	Unit weight (kg/m^3)
RC	165	2325
HRC	157	2155
LRC	153	2068

3.3 Hardened Concrete Mechanical and Physical Results

Compressive strength, splitting tensile strength and hardened state unit weight results of concrete mixes are given in Table 6. Each result is the average of three tests on the concrete samples.

When the results in the Table 5 are examined, it is seen that the compressive strength, splitting tensile strength and unit weight of the 28 days cured concrete mixes change between 45 MPa and 72.7 MPa, 2.85 MPa and 4.05 MPa and 2008 kg/m^3 and 2226 kg/m^3, respectively. Compared with the reference concrete (RC), 7 days compressive strength of HRC and LRC samples were determined to decrease by 10% and 29%, respectively. The 28 days compressive strength of HRC and LRC samples also decreased by 16% and 38%. The results are in accordance with the results presented by Thomas et al., 2018. The authors reported that when 100% of natural aggregates were replaced with recycled concrete aggregate, the compressive strength decreased by 11–19%. The decrease of strength may be due to the low strength of recycled aggregate compared to natural aggregate and also to the porous and cracked structure of the cement mortar layer attached to the recycled aggregate particles (Xu et al., 2017). Due to concrete being a composite material composed by aggregate phase, mortar phase and the interface between the aggregate and the mortar phases, the strength of concrete depends largely on the strength of both phases. Among the three phases, the aggregate phase is the strongest, and it can observed that the higher the aggregate quality the higher the concrete strength. Moreover, Thomas et al. (2018) reported that three types of interfacial transition zones exists in concrete containing RCA, such as, the zone between the original aggregates and the old attached cement mortar, the zone between the old cement mortar and the new cement mortar as well as the zone between the aggregates and the new cement mortar. This presence of more than one interfacial transition zone in RCA concrete, the weakest among the three concrete phases, results in lower strength when compared with natural aggregate concrete.

TABLE 6. Unit weight, splitting tensile strength and compressive strength of the concrete mixes.

Concrete code	Unit weight (kg/m^3)	Splitting tensile strength (MPa)		Compressive strength (MPa)	
		7 days	28 days	7 days	28 days
RC	2226	3.60	4.05	46.5	72.7
HRC	2081	3.22	3.31	41.8	60.8
LRC	2008	2.75	2.85	33.1	45

TABLE 7. Water absorption and porosity of the concrete mixes.

Concrete code	Water absorption (%)		Porosity (%)	
	7 days	28 days	7 days	28 days
RC	6.18	4.44	13.19	9.86
HRC	7.02	5.75	15.26	11.63
LRC	8.98	6.84	18.59	14.32

By analyzing splitting tensile strength results, it is observed that compared with reference concrete (RC), the 28 days splitting tensile strength of HRC and LRC samples decreased by 18% and 30%, whereas the 7 days splitting tensile strength decreased by 11% and 24%. The results obtained from the study are in line with those obtained by Kou et al., 2011. The authors concluded that the splitting tensile strength decreased by 18.8–21.7% when 100% of natural aggregates are replaced with RCA. In general, it is seen that the concrete mixes containing limestone aggregates have a higher compressive and splitting tensile strength than the concrete containing RCA. Also, the decrease of the strength is more significant when RCA are obtained from low strength concrete. The lower splitting tensile strength of HRC and LRC mixes may be attributed to poor bonding between paste and aggregates as well as the presence of weak and porous ITZ in HRC and LRC as compared to RC (Barbudo et al., 2013; Muduli et al., 2019). Furthermore, the inferior property of LRCA as compared to HRCA is responsible of the lower splitting tensile strength of LRC when compared with HRC mixes.

The results of water absorption by immersion and porosity accessible to water of concrete mixes are given in Table 7. Each result is the average of three tests on concrete samples.

The results of water absorption and porosity show that physical properties are altered by the use of coarse RCA. High water absorption and porosity values were obtained in the HRC and LRC rather than in the control mix. Water absorption and porosity increased up to 54% and 45% when coarse limestone aggregate was 100% replaced by LRCA. The more rough and porous structure of RCA surface and the excess water absorption of cement mortar adhered to the surface of the original aggregate may be considered as the cause of the increase in water absorption of the HRC and LRC concrete mixes. The results obtained from the study are in accordance with that obtained by Pedro et al., 2018. The authors reported the water absorption by immersion increased by 26.1–77.2% when 100% of natural aggregates are replaced with RCA. However, several authors reported that the use of mineral additives such as fly ash, silica fume, slag and metakaolin significantly reduces the negative impact of RCA-containing mixtures on water absorption capacity (Mardani-Aghabaglou et al., 2019; Kurda et al., 2019; Çakır, 2014).

4. CONCLUSION

The effects of recycled concrete aggregate (RCA) quality on the fresh and hardened properties of concrete such as workability, fresh unit weight, compressive strength, splitting tensile strength, density, water absorption and porosity accessible to water have been investigated. Based on the experimental results, the following conclusions can be drawn:

- The properties of recycled aggregates derived from lower strength concrete parent (LRCA) and higher strength concrete parent (HRCA) such as water absorption, density, specific gravity and Los Angeles abrasion are of lower quality than that of the limestone aggregate.
- The attached mortar and aggregates content are 61% and 35.5% for LRCA whilst the attached mortar and aggregate contents for HRCA are 45.9% and 53.7%, respectively.
- The fresh unit weight of the concrete mixes decreased up to 7.3% and 11% when coarse limestone aggregate was replaced with coarse HRCA and LRCA, respectively.
- Compared with reference concrete (RC), 7 days compressive strength of HRC (concrete made with HRCA) and LRC (concrete made with LRCA) samples were determined to be decreased by 10% and 29%, respectively. The 28 days compressive strength also decreased by 16% and 38%.
- The decrease of the strength is more significant when RCA are obtained from low strength concrete.
- The 28 days splitting strength of HRC and LRC samples decreased by 18% and 30% whereas the 7 days splitting strength decreased by 11% and 24% in comparison with reference concrete (RC).
- The results of water absorption and porosity showed that the physical properties are altered when natural aggregate is replaced by coarse RCA in concrete.

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