International Journal of Engineering & Technology, 7 (4.37) (2018) 90-97

International Journal of Engineering & Technology

Website: Www.Sciencepubco.Com/Index.Php/IJET

Paper Research

Utilizing Recycled Concrete and Stone Aggregate as Replacement for Natural and Crushed Virgin Aggregate

Zaid Al-Azzawi*

College of Engineering, University Of Anbar, Ramadi, Iraq
**Corresponding author E-mail: zaid.kani@uoanbar.edu.iq*

Abstract

The mechanical properties of recycled concrete aggregate form Al-Anbar province in Iraq is presented in this paper. Recycled concrete and stone aggregates were utilized as replacements for both natural and crushed virgin aggregate. Four series of tests were conducted to study various replacement ratios (0.25, 0.50, 0.75 and 1.0) effect on compressive strength, splitting tensile strength and modulus of rupture. Density of concrete in addition to its water absorption were also investigated. Results of this work show that replacing natural and crushed virgin aggregate with waste concrete aggregate extracted from left-over concrete cubes and concrete barriers did not affect its mechanical properties significantly. In fact, in this study the general trend is that the compressive strength increases with increasing the replacement ratio from 0.0 to 1.0. However, the tensile strength showed different behaviour as there was a limit for the strength increase with replacement ratio where beyond it the strength started decreasing again. This limit varied between 0.50 and 0.75 depending on the type of aggregate used and the type of the test. The age of test did not affect the behaviour of the trialled mixes significantly. In addition to that, recycled stone aggregate proved to be an alternative choice only for lower grade concrete because it reduced both compressive and tensile strength in comparison to the reference mix.

Keywords: *Concrete, Crushed gravel, Mechanical properties, Natural gravel, Recycled concrete aggregate, Recycled stone aggregate*.

1. Introduction

Introduction and Background: Recycling of demolished buildings rubble is not a novel idea and some cases of recycling demolition waste date back to the 2nd World War. In several countries, Europe, Japan and the United States for instance, it is an important process which can be used to produce a good source of aggregate for the construction industry (O'Mahony, 1990). The recycling process is likely to be successful in Al-Anbar province in Iraq because of the massive number of buildings destroyed during the war, which could be a sufficient source for consistent supply of rubble. However, this rubble does not contain concrete only and it contains several other construction materials including stone which is a conventional building material in north and west of Iraq. For this reason, a new type of recycled aggregate extracted from crushed building stone rubble is used in this study in addition to the ordinary recycled aggregate from concrete rubble. After the 2nd World War, approximately eleven million cubic meters of brick were recycled as coarse aggregate for concrete in Germany. In 1951, a standard was introduced for concrete made with recycled aggregate but was withdrawn afterwards and reproduced later to be a standard for lightweight aggregates because the quantity of recycled aggregate available for recycling was dropping down (Schulz, 2004). This standards in its current form is known as DIN 4226 (2011). In Japan, it has been found that the strength of a base-course increases with time if it is constructed using crushed concrete (Yoshikane, 2004). The Resource Centre For Building Excellence (BRANZ) published a study report in 1999 about the use of recycled concrete rubble as aggregate for fresh concrete because there will be a lack of virgin aggregate supplies in New Zealand in the near future. The report conclusion was that the use of recycled concrete rubble as an aggregate for concrete is a possible proposition (Park, 1999). Kou (2006) interestingly showed that recycled aggregates increased the matrix/aggregate interfacial bond strength leading to higher flexural strength and higher fracture energy. He also found that the ultimate strain of recycled concrete aggregate is higher than that of ordinary concrete. It increased with increasing the recycled aggregate content. For concrete with 100% recycled aggregate, the ultimate strain is increased by 20%. Malešev et al. (2010) concluded that regardless of the replacement ratio, recycled concrete aggregate had a good performance, which was not different, significantly, from the performance of ordinary concrete in their work. Spencer (2013) concluded that recycled coarse aggregate (RCA) should be sieved and washed to exclude the fine materials in order to meet Washington State Department of Transportation (WSDOT) requirements for degradation value. Once fines are disclosed, degradation values are found to be almost constant regardless of mixture ratios of RCA with natural aggregate. Results of the work by Tijani (2016) confirmed that, the incorporation of 15% microsilica with 50% recycled coarse aggregate fraction produced 28-day compressive cube strength which exceeds the characteristics and target mean compressive cube strength of the control mix which are 50MPa and 63.1Mpa, respectively. The result suggests that there is a potential to increase the optimum fraction of recycled aggregate from 30-50% in concrete. All the above-mentioned work leads to the conclusion that it is possible to use recycled concrete aggregate to produce concrete that does not differ much in its mechanical properties than concrete made form virgin aggregate. However, to the knowledge of the author, no research addresses the difference in using RCA as a replacement to natural versus crushed virgin aggregate. In addition, the possibility of using recycled stone aggregate is also investigated in this work.

Copyright © 2018 Authors. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

2. Materials And Methods

1. Materials

2.1 Cement: Ordinary Portland cement is used throughout this work. The chemical and physical properties of this cement are presented in Tables 1 and 2, respectively. The test results show that the cement conforms to the Iraqi specifications provision.

2.1.1 Virgin aggregate:

Fine aggregate: Local fine aggregate from Karbala' region in Iraq is used throughout the experimental work in this study. The sand conforms to the Iraqi standards IQS No.45:1984, Zone-1. The sand have a specific gravity of 2.68 and a sulphate content of 0.24% which are both within acceptable limitations. Table 3 shows the sieve analysis for the fine aggregate.

Coarse aggregate: Both natural and crushed aggregate with a maximum size of 20mm and sulphate content ranging between of 0.02% and 0.023% are used in this study, the aggregate conforms to the IQS No. 45:1984. Table 4 and Table 5 respectively show the gradation for the natural and crushed gravel along with their physical properties.

Table 1: Chemical properties of the used cement

Oxide Composition	Content (%)	Limits of Iraqi specifications No.5/1984
CaO	63.30	---
SiO_2	19.22	< 21%
Al_2O_3	4.52	< 8%
Fe_2O_3	3.36	< 6%
SO_3	2.01	≤ 2.5 if C_3A < 5% ≤ 2.8 if C_3A > 5%
MgO	2.63	< 4.0%
Loss of ignition (L.O.I)	2.30	< 4.0%
Insoluble residue (I.R)	0.46	< 1.5%
Free lime	0.95	0.66-1.02
Main Compounds (Bogue's equation)		
C_3S	70.44	---
C_2S	4.28	---
C_3A	6.32	---
C_4AF	10.13	---

Table 2: Physical properties of the used cement

Physical properties	Test result	Limits of Iraqi specifications No.5/1984
Specific surface area (Blaine/ cm^2/ gr)	3540	> 2300
Initial setting, hr. : min Final setting, hr. : min	2:31 5:18	≥ 0:45 ≤ 10:00
Compressive strength 3 days, N/mm^2 7 days, N/mm^2	 20.60 26.12	 ≥ 15 ≥ 23

Table 3: Sieve analysis of fine aggregate

Sieve size (mm)	Percent passing	Limits of Iraqi Specifications No. 45:1984, Zone-1
10	100	100
4.75	89.2	90-100
2.36	65.2	60-95
1.18	51.6	30-70
0.6	30.9	15-34
0.3	7.7	5-20
0.15	0.6	0-10

Table 4: Sieve analysis of natural virgin gravel

Sieve size (mm)	Percent passing	Limits of Iraqi Specifications No.45:1984
37.5	100	100
20	97.7	95-100
10	31.1	30-60
5	0.53	0-10
Physical properties		*Maximum allowable limits*
Specific gravity test	2.59	-
Los Angles test	22.3%	30%
Absorption test	2.32%	5%

Table 5: Sieve analysis of crushed virgin gravel

Sieve size (mm)	Percent passing	Limits of Iraqi Specifications No. 45:1984
37.5	100	100
20	98.1	95-100
10	28.4	30-60
5	2.33	0-10
Physical properties		*Maximum allowable limits*
Specific gravity test	2.55	-
Los Angles test	25.2%	30%
Absorption test	2.86%	5%

2.1.3 Recycled course aggregate:

Three types of recycled aggregate are used in this study depending on their source. Recycled concrete aggregate (RCA) extracted from left-over concrete cubes (Type-A), RCA coming from left over concrete barriers (Type-B), and recycled aggregate resulting from destroyed building stone rubbles (RSA). The compressive strength of the left-over concrete cubes where in the range of 31-35 MPa. 100 mm stone cubes where made from the stone rubbles to estimate its compressive strength which ranged between 18 and 32 MPa. Unfortunately, the compressive strength of the barriers was difficult to be determined without a core test which was not available at the time. In all cases, the rubbles were crushed mechanically to produce the required amount of recycled aggregate. An effort is made to produce recycled aggregate as close as possible to the Iraqi standards for virgin aggregate because there are no Iraqi standards dedicated for RCA yet. This is also due to consistency requirements, so that the results of the different series can be compared without distortion coming from differences in the grading of the aggregate. Table 6 shows limited divergence in the grading and physical properties of the three types of recycled aggregate used in this work. Fig. (1) shows some photos for the used virgin and recycled aggregate and a sample of the 100 mm stone cube made out of stone rubbles in addition to the crashing machine.

Table 6: Properties of recycled aggregate

Sieve size (mm)	Percent passing			Limits of Iraqi Specifications No.5: 1984
	RCA Type-A	*RCA Type-B*	*RSA*	
37.5	100	100	100	100
20	98.7	99	95	95-100
10	21.1	19	34	30-60
5	0.53	1	17	0-10
Physical properties				*Maximum allowable limits*
Specific gravity test	2.51	2.49	2.34	-
Los Angles test	31.3	34.2	51.0	30%
Absorption test	2.94	3.21	3.84	5%



(**a**) Natural virgin gravel (**b**) Crushed virgin gravel



(**c**)Recycled concrete aggregate (**d**) Recycled Stone Aggregate



(**e**) Recycled stone cube (**f**) Crushing machine

Fig. 1: Photos showing different types of aggregate used in this experimental study.

2.2 Test variables and mix proportions : In this study the possibility of using different recycled coarse aggregate types with different replacement ratios ranging from 0.0 to 1.00 as a replacement for both virgin natural and crushed aggregate is investigated. Four series of tests were performed, Series-A included using RCA extracted from left-over concrete cube specimens as a replacement for natural virgin gravel while series-B used the same source of RCA but with crushed virgin gravel. Series-C included RCA extracted from concrete rubbles coming from left-over concrete barriers, and finally series-D investigated the possibility of using recycled stone aggregate (RSA) as a partial replacement for crushed virgin gravel. Table 7 shows the test variables investigated in the current work. The used mix proportions by weight is 1.0:1.5:3.0:0.45 for the cement, sand, gravel and water, respectively. This mix is adopted throughout this work because it is well established in practical applications in Iraq. The cement content is 413 kg/m^3 for workability and strength criteria.

Table 7: Test variables

Ref.	Series	Virgin aggregate	Recycled aggregate	Replacement ratio %
A0.00	Series-A	Natural	RCA: Type-A	0.0
A0.25	Series-A	Natural	RCA: Type-A	25
A0.50	Series-A	Natural	RCA: Type-A	50
A0.75	Series-A	Natural	RCA: Type-A	75
A1.00	Series-A	Natural	RCA: Type-A	100
B0.00	Series-B	Crushed	RCA: Type-A	0.0
B0.25	Series-B	Crushed	RCA: Type-A	25
B0.50	Series-B	Crushed	RCA: Type-A	50
B0.75	Series-B	Crushed	RCA: Type-A	75
B1.00	Series-B	Crushed	RCA: Type-A	100
C0.00	Series-C	Crushed	RCA: Type-B	0.0
C0.25	Series-C	Crushed	RCA: Type-B	25
C0.50	Series-C	Crushed	RCA: Type-B	50
C0.75	Series-C	Crushed	RCA: Type-B	75
C1.00	Series-C	Crushed	RCA: Type-B	100
D0.00	Series-D	Crushed	RSA	0.0
D0.25	Series-D	Crushed	RSA	25
D0.50	Series-D	Crushed	RSA	50
D0.75	Series-D	Crushed	RSA	75
D1.00	Series-D	Crushed	RSA	100

2.2 Mixing and casting procedures:

All mixing materials are weighed and prepared before starting the mixing process. A pan mixer is used in this study. First, gravel and sand are poured into the mixer and mixed for two minutes and then the cement is poured and mixing continued for another two minutes. After getting a homogenous dry mix, the water is added gradually and mixing continued for another 3-5 minutes depending on visual inspection. Afterward, a slump test is conducted and the concrete is cast using the pre-prepared moulds. Fig. (2) shows photos for the mixer and a slump test during action.



(**a**) Mixing of concrete (**b**) Slump test

Fig. 2: Photos showing mixing of concrete and the slump test

2.4 Test Specimens and Instrumentation

From each mix, nine 150mm cubes, nine 150×300mm cylinders and nine 100×100×400mm prisms are cast, three specimens out of the nine are tested at ages of 3, 7 and 28 days, respectively for compressive strength, splitting tensile strength and modulus of rupture. The concrete is poured into the moulds in three approximately equal layers, each layer is compacted with a square compacting rod by at least 25 strokes. The specimens are left to dry for at least 24 hours and then de-moulded and moved to curing water tanks. Fig. (3) shows specimens during casting and after de-moulding. The compression test is conducted in accordance to BS 1881, the splitting tensile strength is performed according to the ASTM C496 and the flexural test is conducted using third point prism test according to the ASTM C78 to determine the modulus of rupture. Fig. (4) shows photos for the three tests.

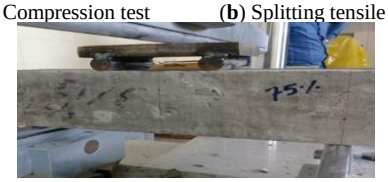


(**a**) Casting the moulds (**b**) Specimens from each batch

Fig. 3: Photos for specimens during casting and after de-moulding.



(**a**) Compression test (**b**) Splitting tensile test



(c) Flexure third point test

Fig. 4: Photos showing testing the specimens for their mechanical properties

3. Results and Discussions

Experimental Results and Discussion

In the current study, the possibility of utilizing recycled concrete and stone aggregate as a partial replacement for natural and crushed virgin aggregate is investigated throughout four series of tests, refer to Table 7 to see the details of the test series and the types of virgin and recycled aggregate used.

In the following sections the experimental results of this study are illustrated and discussed in details. Tables 8 through 10 show the mechanical properties of all tested specimens in this work at different testing ages (3, 7 and 28 days). In addition, density and water absorption capacity are illustrated in Table 11 for concrete mixes at an age of 28 days. It is worthwhile emphasizing that each point in the results is the average of three tests.

3.1 Compressive strength:

Table 8 shows the results of the compression tests for all four series in this work at different testing ages of 3, 7 and 28 days. From Table 8 and Fig. (5), it can be seen that there are different patterns of behaviour depending on the age of test, the used virgin aggregate, the type of recycled aggregate and its partial replacement ratio. Fig. (5) shows the change in the compressive strength with increasing the replacement ratio for different age of tests (3, 7 and 28 days). Form this figure it can be seen that, in spite of the fluctuation in the strength values up and down with the replacement ratio reflecting a non-linear behaviour, the general trend is that the compressive strength increases with increasing the RCA content (replacement ratio) independent from the type of the RCA used, however to different extents. The maximum compression strength increase at 28 days was 82% from its corresponding control mix for series-A (type-A RCA) having a replacement ratio of 1.00, while the minimum strength increase at 28 day is 31% for series-B (type-A RCA) with a replacement ratio of 1.00. This high strength increase in series-A may be justified by the fact that the natural gravel is replaced with crushed recycled gravel which has higher bond characteristics in addition to the possibility of the extra hydration resulting from the cement paste attached to the RCA because its source was left-over concrete cubes with an average age of one year, giving the possibility of increasing the cement content in the recycled mix. For the other series of RCA (series-B and C), the virgin gravel was already crushed reducing the rate of strength increase to the factor of increasing the cement content only which is limited. However, for series-D (RSA), the concrete behaved in a different way where the strength decreased with increasing the replacement ratio almost linearly. The maximum drop in the strength at age of 28 days was 35% with a replacement ratio of 1.0 compared to the reference mix. This might be attributed to the fact that RSA has a very high Los Angles test value of 51% which is much higher than the limit of 30% specified by the Iraqi standards as can be seen in Table 6.

3.2 Splitting tensile strength : Table 9 shows the results of the splitting tensile tests for all four series in this work at different testing ages of 3, 7 and 28 days. From Table 9 and Fig. (6), it can be seen that there are different patterns of behaviour depending on the age of test, the used virgin aggregate, the type of recycled aggregate and its partial replacement ratio.

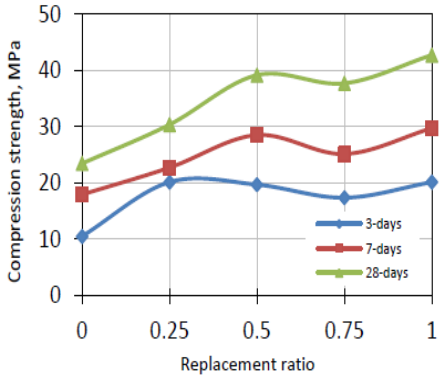
Fig. (6) shows the change in the tensile strength with increasing the replacement ratio for different age of tests (3, 7 and 28 days). Form this figure it can be seen that, in spite of the waving in the strength values up and down with increasing the replacement ratio, the general trend is that the tensile strength increases with increasing the RCA content up to a certain replacement ratio limit. This limit varied depending on the replacement ratio and the type of RCA. In general, this replacement ratio limit ranged between 0.50-0.75 where after the tensile strength started decreasing again to a value close to the corresponding control mix. The maximum increase in the tensile strength is 90% with respect to its corresponding control mix, which took place in series-A (Type-A RCA) having a replacement ratio of 0.75. Both series-B (Type-A RCA) and series-C (Type-B RCA) have the same maximum strength increase of approximately 35% with a replacement ratios of 0.50 and 0.75, respectively. This difference in the optimum replacement ratio between the compressive and tensile strengths for the same mix may be attributed to the structure of microcracks and loading pattern. Different types of aggregate having different specific gravity values are present in the same mix, this may cause further microcracking leading to weaker transition zones which will affect the tensile behaviour far more than the compressive behaviour because of the way the stress is applied mechanically. In the tension case, the stress is applied perpendicular to the crack plane causing rapid collocation of the microcraks leading to a sudden (brittle) failure. For series-D (RSA), the strength dropped right from the beginning and continued decreasing with increasing the replacement ratio almost linearly. The maximum drop at an age of 28 days was 16% resulting from a replacement ratio of 1.0.

Table 8: Test results of compressive strength

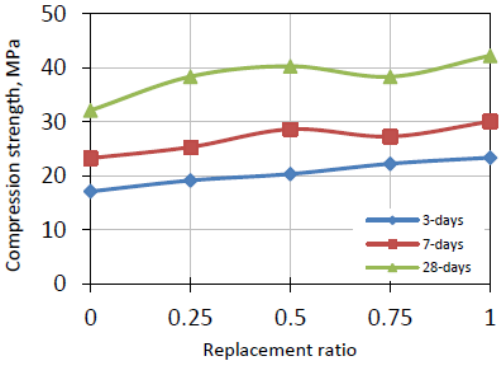
Ref.	Compressive strength, MPa		
	3-days	*7-days*	*28-days*
A0.00	10.46	17.86	23.43
A0.25	20.1	22.67	30.33
A0.50	19.66	28.49	39.12
A0.75	17.33	25.11	37.67
A1.00	20.1	29.71	42.68
B0.00	17.11	23.23	32.1
B0.25	19.13	25.3	38.33
B0.50	20.32	28.62	40.25
B0.75	22.21	27.26	38.31
B1.00	23.34	30.05	42.2
C0.00	13.87	21.09	32.28
C0.25	18.08	24.5	34.79
C0.50	14.17	25.37	37.31
C0.75	17.07	28.64	42.68
C1.00	19.89	29.22	45.13
D0.00	13.23	25.42	31.65
D0.25	12.1	16.72	25.12
D0.50	11.22	16.25	22.31
D0.75	11.31	16.19	21.22
D1.00	9.42	14.31	20.5

Table 9: Test results of splitting tensile strength

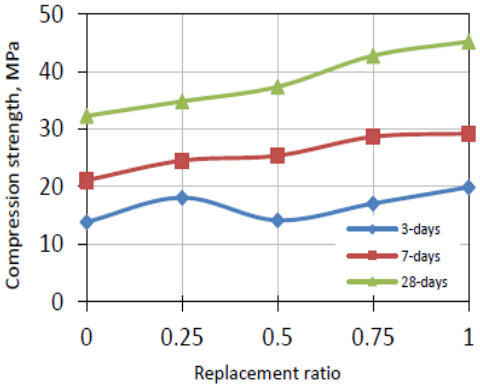
Ref.	Splitting tensile strength, MPa		
	3-days	*7-days*	*28-days*
A0.00	1.12	1.43	1.65
A0.25	1.54	2.4	2.6
A0.50	1.62	2.39	3.01
A0.75	1.39	2.08	3.13
A1.00	1.18	1.73	2.51
B0.00	1.48	1.81	2.03
B0.25	1.55	2.03	2.44
B0.50	1.56	2.16	2.75
B0.75	1.33	1.89	2.66
B1.00	1.23	1.76	2.56
C0.00	0.92	1.41	2.16
C0.25	1.2	1.62	2.31
C0.50	1.24	1.87	2.66
C0.75	1.2	2.01	2.99
C1.00	1.09	1.88	2.65
D0.00	1.21	1.81	2.62
D0.25	1.32	1.63	2.55
D0.50	1.25	1.45	2.43
D0.75	1.15	1.53	2.37
D1.00	1.07	1.37	2.2



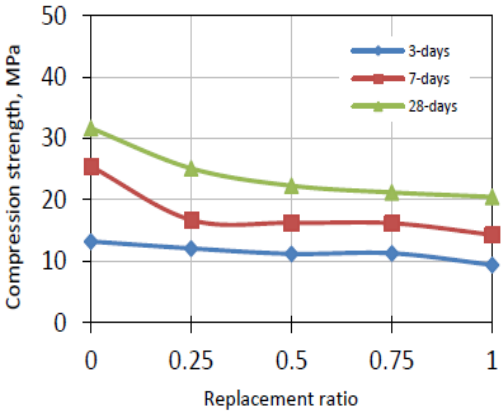
Series-A



Series-B

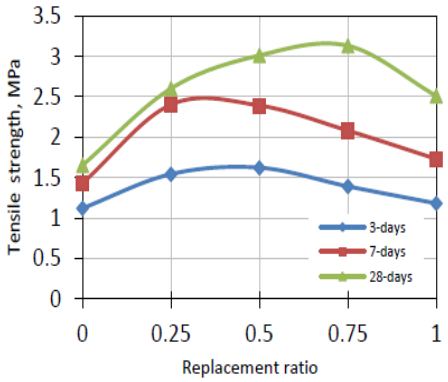


Series-C

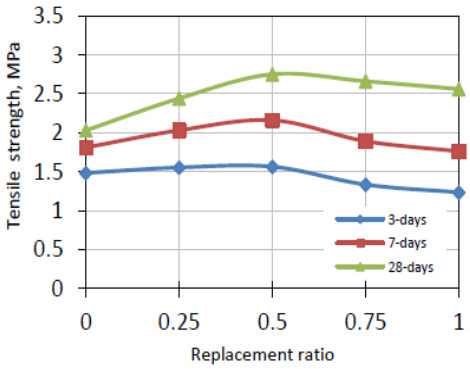


Series-D

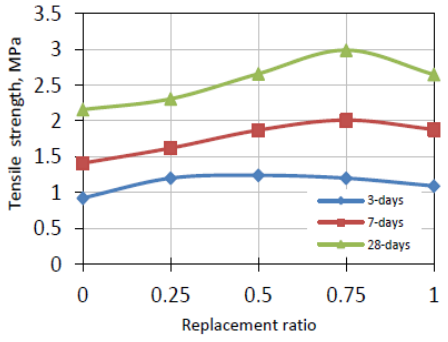
Fig. 5: Variation of compressive strength with replacement ratios



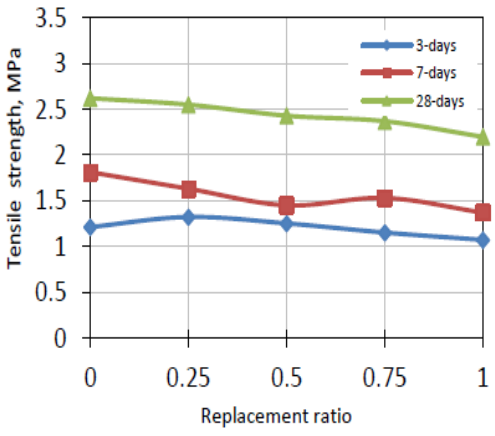
Series-A



Series-B



Series-C



Series-D

Fig. 6: Variation of Splitting strength with replacement ratios.

3.2 Flexural strength:

Table 10 shows the results of the modulus of rupture tests for all four series in this work at different testing ages of 3, 7 and 28 days. From Table 10 and Fig. (7), it can be seen that there are different patterns of behaviour depending on the age of test, the used virgin

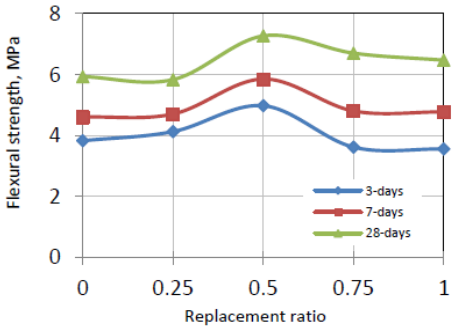
aggregate, the type of recycled aggregate and its partial replacement ratio.

Fig. (7) shows the change in the flexural strength with increasing the replacement ratio for the same age of test (3, 7 and 28 days). Form this figure it can be seen that the general trend is that the flexural strength increases insignificantly with increasing the RCA content up to a replacement ratio limit of 0.5. Afterward the flexural strength started decreasing again to a value close to the corresponding control mix. This behaviour reflects that RCA have no significant effect on the flexural strength of the trialled mixes.

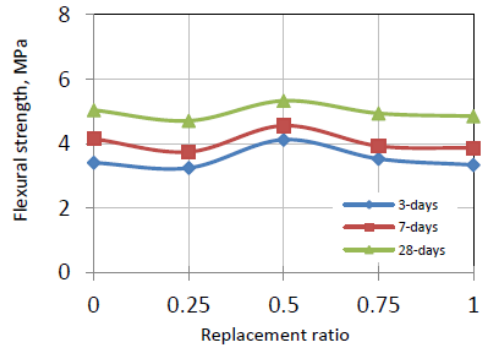
For series-D (RSA), the flexural strength followed the same pattern of the compressive and splitting tensile strength where it decreased almost linearly with increasing the replacement ratio. The maximum drop in the strength is 34% with a replacement ratio of 1.0.

Table 10: Test results for modulus of rupture

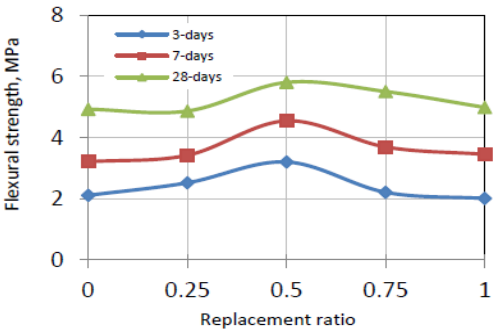
Ref.	Modulus of rupture, MPa		
	3-days	*7-days*	*28-days*
A0.00	3.83	4.6	5.93
A0.25	4.13	4.7	5.83
A0.50	4.98	5.85	7.27
A0.75	3.62	4.8	6.7
A1.00	3.56	4.77	6.47
B0.00	3.41	4.15	5.04
B0.25	3.25	3.75	4.71
B0.50	4.12	4.56	5.33
B0.75	3.53	3.93	4.94
B1.00	3.34	3.87	4.85
C0.00	2.11	3.21	4.92
C0.25	2.52	3.42	4.86
C0.50	3.2	4.54	5.8
C0.75	2.21	3.69	5.5
C1.00	2.01	3.45	4.98
D0.00	3.42	4.98	6.23
D0.25	3.17	4.34	5.51
D0.50	2.64	4.22	5.25
D0.75	2.5	3.35	4.53
D1.00	2.21	3.33	4.12



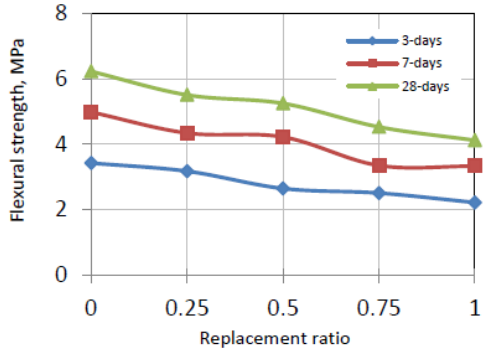
Series-A



Series-B



Series –C



Series-D

Fig. 7: Variation of Flexural strength with replacement ratios

3.3 Density of concrete and water absorption:

Table 11 shows the distribution of density of concrete and its water absorption according to their mix designations at an age of 28-days. Fig. (8) illustrates the variation in the density of concrete specimens with the replacement ratio as a function of the type of virgin and /or recycled aggregate. It can be seen that the density of concrete typically decreases linearly with increasing the replacement ratios for RCA. One exception of this is series-D (RSA) where the density decreased in a steeper manner from a density of 2435 to 2208 kg/m^3. the maximum reduction in the density in this work is approximately 5% for all series at an age of 28 days except for series-D (RSA) where the maximum reduction was 10%. This reduction in the density of concrete could be attributed to the lower specific gravity of the recycled aggregate and the more the replacement ratio, the more the reduction in the density is resulted.

The water absorption of the concrete mixes for all four series in this study can also be found in Table 11. Fig. (9) shows the variation of water absorption with the replacement ratio as a function of the type of the virgin and recycled aggregate used. From this figure it can be seen that the water absorption is typically reduced with increasing the replacement ratio, the maximum reduction was 88% for series-B (type-A RCA) followed by 59% and 28% for series-A (Type-A RCA) and series-C (type-B RCA), respectively. One exception for this typical behaviour is series-D which had RSA instead of RCA, in this series the water absorption increased with increasing the replacement ratio up to 18% for a replacement

ratio of 1.0. This could be justified by the type of the aggregate used which is a stone aggregate and have higher absorption capability.

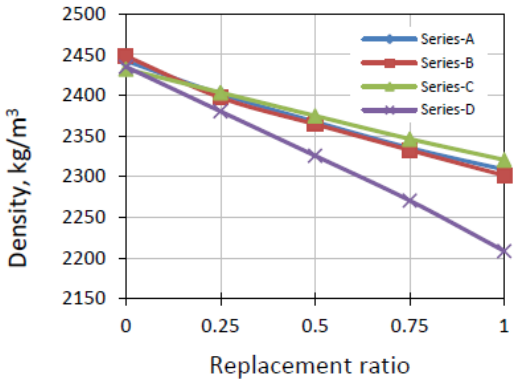


Fig. 8: Variation of density of trialled mixes

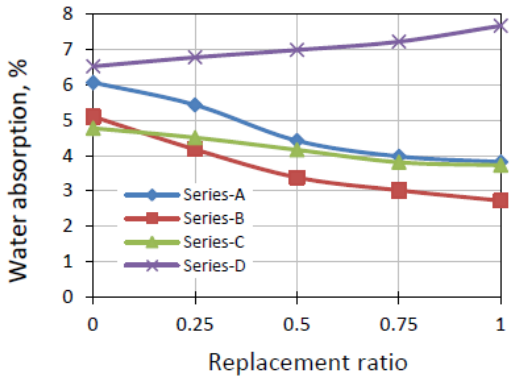


Fig. 9: Variation of water absorption of concrete

Table 11: Density and water absorption of concrete specimens at 28 day

Ref.	Density, kg/m³	Water absorption %
A0.00	2442.2	6.07
A0.25	2401.4	5.43
A0.50	2367.3	4.42
A0.75	2335.2	3.98
A1.00	2308.5	3.82
B0.00	2448.4	5.10
B0.25	2397.2	4.17
B0.50	2364.4	3.38
B0.75	2332.5	3.01
B1.00	2301.3	2.72
C0.00	2432.1	4.77
C0.25	2403.2	4.51
C0.50	2374.5	4.16
C0.75	2346.1	3.81
C1.00	2320.3	3.73
D0.00	2435.1	6.53
D0.25	2380.2	6.78
D0.50	2325.6	6.99
D0.75	2270.5	7.23
D1.00	2208.3	7.68

4. Conclusions

The current study investigated the possibility of using recycled concrete aggregate (RCA) and recycled stone aggregate (RSA) as a partial replacement for natural and crushed virgin aggregate within Al-Anbar region in the west of Iraq. Four series of tests are implemented using multiple combinations of different types of recycled and virgin aggregate to study their mechanical properties. The following conclusions can be drawn from the experimental work:

The compressive strength increases with increasing the RCA replacement ratio. An increase in the compressive strength of 31% to 82% is reported in this study with an RCA replacement ratio of 1.0, depending on the type and combination of virgin and recycled aggregate used. The highest increase resulted from replacing the natural gravel with 100% Type-A RCA.

There is a limit for the increase in the tensile strength represented by both splitting tensile strength and modulus of rupture. In both cases, the tensile strength increased with increasing the replacement ratio up to a limit ranged between 0.50 - 0.75, where after the strength deteriorated back close to the original strength of the corresponding reference mix. Hence, the decision of what replacement ratio should be used may be taken based on the function of the structural member under design consideration. If compression is dominating the design, 100% replacement ratio may be used. Otherwise the limit of 0.5 can be considered.

In this study, the general trend was that the density is reduced with increasing the replacement ratio almost linearly. A maximum reduction of 10% is recorded for series-D with a replacement ratio of 1.0.

Water absorption is typically reduced with increasing RCA replacement ratio for all series of tests apart from series-D where the water absorption increased with increasing the RSA replacement ratio.

In general, RSA can be considered as an alternative to RCA in cases where eco-friendly concrete is intended having low to medium strength and density requirements.

To conclude the paragraph, using both RCA and RSA is possible for concrete industry within the area investigated in this study. As a matter of fact, after performing some further studies including long term behaviour, using RCA and/or RSA could be considered a viable alternative resource of aggregate which have some economical and environmental advantages such as saving the raw materials and enhancing the mechanical properties of concrete in the case of RCA.

Acknowledgment

I would like to express my gratitude and appreciation for all the faculty members, lab staff and students who helped me in finishing this work. Eng. Shamil Kamel, Eng. Mohammed Qasem, Eng. Abdulkhaliq Maree, Eng. Emad Jasem, Eng. Amjad Abdulrahman, and Eng. Jamal Ali. Also the advice and recommendations of Dr. Abdulkader Al-Hadithi and Dr. Ahmed Tareq are highly appreciated. Thanks is due to the Civil Engineering Dept. for providing the lab and requi.

References

[1] ASTM Standard C496 (2004). Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.
[2] ASTM Standard C78 (2002). Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading).
[3] Boyle S. (2013). Evaluation of recycled concrete for use as aggregates in new Portland cement concrete pavements. MSc. Washington State University. pp. 108.
[4] British Standards Institution (2003). BS 1881: Part 116: Method for determination of compressive strength of concrete cubes.
[5] Iraqi standard specifications No.45/1984, Natural resources aggregate used in concrete and buildings.
[6] Iraqi standard specifications No.5/1984: Portland cement.

[7] Kou S. (2006). Reusing recycled aggregate in structural concrete. PhD Thesis. The Hong Kong Polytechnic University. 313 pp.
[8] Malešev M., Radonjanin V. and Marinković, S. (2010). Recycled concrete as aggregate for structural concrete production. Sustainability. :204-1225.
[9] O'Mahony M. (1990). Recycling materials in civil engineering. PhD Thesis, University of Oxford. 233 pp.
[10] Park S.G. (1999). Recycled concrete construction rubble as aggregate for new concrete. Building Research Association of New Zealand. Study Report SR 86. Judgeford.
[11] Schulz R.R. (2004). Concrete with recycled rubble-developments in West Germany. Proc. 2nd International RILEM Symposium. Demolition and Reuse of Concrete and Masonry.2. Reuse of demolition waste. Japan.
[12] Tijani A.I. (2016) High performance recycled aggregate concrete incorporating micro silica and synthetic macro fibre. PhD Thesis. University of Birmingham. 276 pp.
[13] Yoshikane T. (2004). The instances of concrete recycled for base course material in Japan. Proc. 2nd International RILEM Symposium. Demolition and Reuse of Concrete and Masonry. 2. Reuse of demolition waste. Japan.