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Research Article

Use of crushed bricks and recycled concrete as replacement for fine and coarse aggregates for sustainable concrete production

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ABSTRACT

The growing concern over the significant ecological changes requires sustainable developments in all fields. Concrete production is one of the largest consumers of natural resources as it consumes a huge volume of natural fine and coarse aggregates, which constitute 70% - 80% of the concrete volume. It is evident that such large amount of concrete production in the growing construction industry puts significant impact on the use of natural resources and the environment. Hence, investigating the use of recycled materials to replace the finite natural resources became evident and is the focus of researchers. In this research, the use of waste crushed bricks (CB), and crushed recycled concrete (CRC) as a partial replacement of fine and coarse aggregates in concrete was studied. The replacement ratios of 10%, 50%, and 100% by weight of either fine or coarse aggregates were used. Eight concrete mixes with 168 specimens were tested for compressive, splitting tensile as well as, flexural strength. All tests were carried out at ages of 7, 28 and 56 days. The results indicated that there is a feasibility of using bricks and concrete wastes in concrete mix as a partial replacement of course and fine aggregates. It is deduced that a 50% replacement ratio of coarse aggregate with crushed concrete resulted in a 30%, 25%, and 23% increase in compressive, tensile, and flexural strengths, respectively. While 50% replacement ratio of fine aggregate with crushed bricks resulted in a 23%, 28%, and 19% increase in compressive, tensile, and flexural strengths, respectively. The most effective mix was at 50% replacement ratio of coarse aggregate with crushed concrete in combination with 50% replacement ratio of fine aggregate with crushed bricks. The results of this mix showed 32%, 28%, 26% increase in compressive, tensile, and flexural strengths, respectively.

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1. Introduction

Concrete is a composite material composed of aggregates, chemically bound together by hydrated Portland cement. These aggregates strongly influence concrete's freshly mixed and hardened properties, mix proportions, and economy (Sajan et al. 2022; Francesco et al. 2021).

In the last decade, amount of construction waste has considerably increased due to the demolition of old structures (Kirthika et al. 2022). With the growing new construction and re-construction of buildings to improve the living standard, the reserves of natural aggregates depleted rapidly (Mohamed et al. 2021). Hence, social, and environmental pressures have driven the use of recycled wastes to partially replace the natural resources (Maciej et al. 2023). The application of recycled concrete aggregate has sometimes remained limited to low valued purposes such as road base materials due to the unstable supply of the waste to the recycling facilities and the fact that the recycling techniques was not satisfactory to produce a good quality recycled waste (Dang et al. 2020; Kazemian et al. 2019).

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With the improvement of the recycling techniques, the use of recycled materials has become the focus of researchers as a viable replacement of natural resources (Abdulkadir et al. 2020; Zheng et al. 2018).

Many researchers concluded that recycled materials can be used as aggregates in new concrete, which offer a viable route to convert the waste to a valuable resource (Yang 2018; Pan et al. 2020). Shruthi (2018) studied the effect of using crushed brick powder as a partial replacement of sand on the properties of concrete. They concluded that the maximum compressive strength is obtained when 40% of brick powder was replaced with fine aggregate.

The effect of different types of recycled concrete aggregates (RCAs) on the equivalent concrete strength and drying shrinkage properties was analyzed by (Memon et al. 2022). Their conducted test results showed that the concrete with RCAs exhibited compressive strength, modulus of elasticity, and flexural strength values equivalent, within 2% variation, to those values of the companion natural aggregate concrete.

Tiwari et al. **(**2016) studied replacement of recycled coarse aggregates with natural coarse aggregates in concrete by ratios of 0%, 50% and 100%. They found an increase of compressive strength by 27%, and 34% at 50%, and 100% replacement ratios, respectively.

According to the investigation made by Siva et al. (2017) of replacing varying percentage of fine aggregates by crushed spent fire bricks with varying percentage of 10%, 15%, 20% & 25% and optimum percentage of replacements is made and strength and workability parameters are studied. The workability of concrete gets decreased with the addition of the crushed spent bricks, and the maximum strength was gained at 20% replacement ratio compared to conventional concrete.

On the other hand, there are several studies stated reduction in concrete strengths incorporating crushed brick (CB) as a replacement of the natural fine aggregate (NFA) or crushed recycled concrete (CRC) as a replacement of natural coarse aggregate (NCA) (Cuesta et al. 2022; Tamashiro et al. 2022). Even in full scale reinforced concrete elements, when Mahdi et al investigated the effect of using concrete mix with 100% recycled concrete aggregate, they found that ultimate flexural strength decreased with higher deflection corresponding to that of natural aggregates (Mahdi et al. 2023).

The present research focused on the use of CB and CRC as an alternative solution for natural fine and coarse aggregates with the aim of adding to the knowledge in this filed which may lead to a more confidence in using of recycled building materials. The effect of using different percentages CB and CRC as replacement for the fine and coarse aggregate in the concrete mix was experimentally investigated and the optimum percentage of replacement that results in the best possible mechanical properties of produced concrete was proposed.

2. Experimental Program

Th**e** experimental program of the present research consisted of testing **e**ight concrete mixes with different percentages of replacement materials namely: 0% (control mix), 10%, 50%, and 100% for each of CB as fine aggregates and CRC as coarse aggregates. Three mixes containing fine aggregates substitutions, other three mixes containing coarse aggregates substitutions. While the last mix containing both fine and coarse aggregates substitutions by equal percentages of 50%. A total of 168 specimens were cast and tested for compressive, splitting tensile as well as, flexural strengths. All tests were conducted in this study were according to American Standard Specifications for Testing and Materials (ASTM).

2.1. Materials

Different materials were used in the present experimental program; natural fine aggregates (NFA), coarse aggregates, cement, crushed bricks (CB), and crushed recycled concrete (CRC).

2.1.1. Cement

CEM Type I normal Portland cement was used with a specific gravity of 3.15. The cement specifications are according to ASTM C150/2007, and presented in Tables 1 and 2.

Table 1. Chemical composition of cement (OPC-CEM I).

Chemical composition	SIO_2	AL_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_2	LOI
O.P.C	20.1%	4.9%	2.5%	65%	3.1%	2.3%	0.2%	0.4%	0.21%	< 0.9%	2.4%

Table 2. Physical properties of cement (OPC-CEM I).

Property	Test results	Specification limits
Fineness in terms of specific surface area (cm^2/gm)	3120	> 2500
Initial setting time (min.)	100	> 45
Final setting time (hrs.)	5.0	< 10

2.1.2. Natural fine aggregates

Natural siliceous river sand (NS) with a fineness modulus of 2.7, a saturated surface dry specific gravity of 2.6. It is grading is shown in Table 3 and Fig. 1.

2.1.3. Crushed brick (CB) as fine aggregate replacement

The used crushed bricks had fineness modulus of 2.5, specific gravity of 2.65 and absorption of 1.8 percent. It was prepared by crushing bricks and then controlled to have the same grading of the corresponding natural fine aggregates (sand).

Table 3. Grading of the used fine aggregates.

Sieve size (mm)	Grading % passing	Specification limits (ASTM C33) % passing
4.75	100	95-100
2.36	97.40	80-100
1.18	88.90	50-85
0.61	59.08	25-60
0.31	22.18	5-30
0.16	1.70	0-10

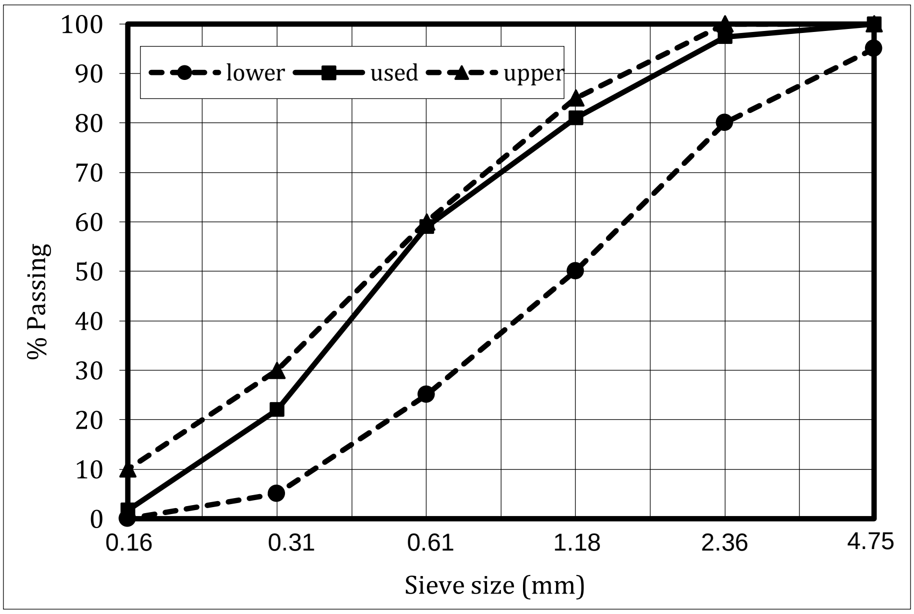

Fig. 1. Grading of the used fine aggregates.

2.1.4. Coarse aggregates

Natural dolomite from Gabal Ataa in Suez area was used as coarse aggregate. The dolomite has a nominal maximum size of about 14 mm. It was washed carefully before mixing to remove any impurities and organic matter which may weaken its bond with the cement paste, also it was immersed in water for about 24 hours, then dried in the air for another 24 hours to reach the saturated and surface dry condition. Grading of the used dolomite is shown in Table 4 and Fig. 2.

Table 4. Grading of the used coarse aggregates.

Sieve size (mm)	Grading % passing	Specification limits (ASTM C33) % passing
20	100	100
14	100	90-100
10	70	40-70
4.75	5.3	0.0-15
2.36	0.0	0.0-5

2.1.5. Crushed recycled concrete as coarse aggregate replacement

Crushed recycled concrete was collected from old concrete samples in laboratory. It was controlled to maximum nominal size of 14 mm and prepared carefully to be saturated surface dry condition. In addition, its grading was controlled to be as same as that of dolomite coarse aggregates.

The physical properties tests of the four types of aggregates were conducted according to ASTM standards, and their results are shown in Table 5.

2.1.6. Water

Ordinary tap water was used in the present research, with cement /water ratio of 0.45.

2.2. Mix design and preparation

The mix design was done in accordance with ACI 211 using the absolute volume method. The W/C ratio was kept constant at 0.45 for all mixes. Eight concrete mixes were prepared with cement content of 400 kg/m^3 in the current research. The first mix (Mc) represents the control mix with natural fine and coarse aggregates. The other three mixes represent the mixes with CB as a partial replacement of sand by ratios of (10, 50, and 100) %. The followed three mixes represents the mixes with CRC replacing the dolomite coarse aggregates by different percentages of 10, 50, and 100%. Based on the compressive strength results of the previous mixes, the last mix was designed to indicate the best possible replacing ratios of CB and CRC in concrete mixes. It represents the mix which contain both replacing materials: 50% of sand aggregate was replaced with CB, and 50% of dolomite coarse aggregate was replaced with CRC. Table 6 shows the details of the mix for each of the eight mixes.

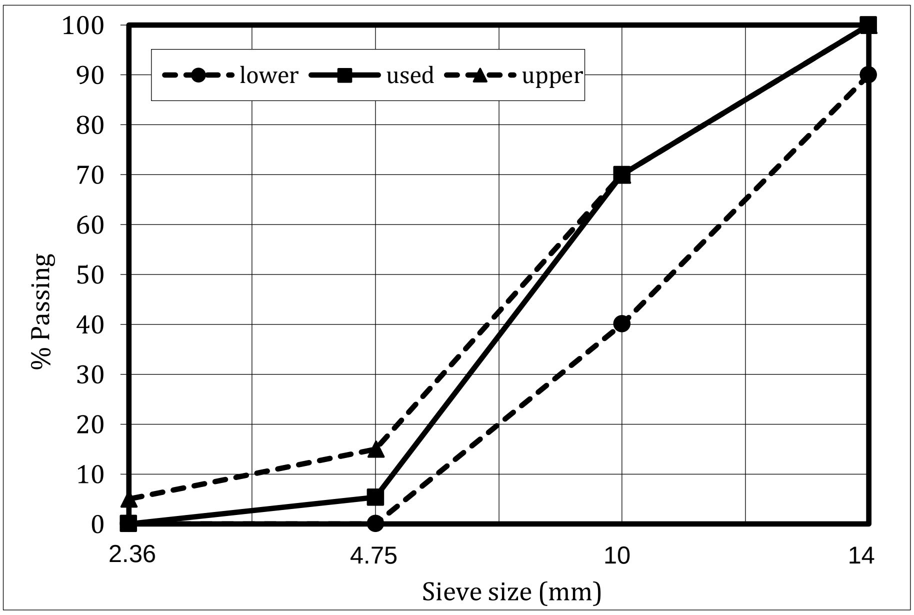

Fig. 2. Grading of the used coarse aggregates.

Table 5. Physical properties of aggregates.

Properties		Volume weight (t/m³) ASTM C29	Specific gravity ASTM C172	Void Ratio %	% Absorption	Fineness modulus
Fine aggregate	NS	1.73	2.6	33.46	2.00	2.7
	CB	1.50	2.5	40.00	5.60	2.5
Coarse aggregate	CD	1.60	2.7	40.60	1.80	6.2
	CRC	1.90	2.7	23.00	0.95	5.5

Table 6. Composition of the concrete mixes (m³).

Mix designation	NS (kg/m³)	CD (kg/m³)	CB (kg/m³)	CRC (kg/m³)	Cement (kg/m³)	W/C ratio
M_c	624	1248	0	0	400	0.45
$M_{(10\% B)}$	561.5	1248	62.5	0	400	0.45
$M_{(50\% B)}$	312	1248	312	0	400	0.45
$M_{(100\% B)}$	0	1248	624	0	400	0.45
$M_{(10\% R)}$	624	1123	0	125	400	0.45
$M_{(50\% R)}$	624	624	0	624	400	0.45
$M_{(100\% R)}$	624	0	0	1248	400	0.45
$M_{(50\% B+50\%R)}$	312	624	312	624	400	0.45

2.3. Test specimens

Cubes of dimensions 100 mm were used to determine the compressive strength, cylinders of dimensions 150x 300 mm were used to determine indirect tensile strength (splitting test), and beams of dimensions 100x100x500 mm were used to determine the flexural strength. The concrete mechanical properties were determined at 7, 28, and 56 days after cast of the test specimens. Fig. 3 shows the test specimen during casting.

The specimens were de-molded 24 hours after the casting, and then were cured in water for 7, 28 and 56 days till the time of testing. Three samples were cast for every single test parameter and the average of obtained test results has been recorded. A total of 168 test specimens were tested in the present research.

3. Results and Discussion

Table 7 shows the obtained results for compressive strength, tensile strength, and flexural strength for all mixes.

Fig. 3. Shapes of test molds: cubes, cylinders, and beams.

Table 7. Test results.

Mix Designation	Compressive strength (MPa)	% Change	Tensile strength (MPa)	% Change	Flexural strength (MPa)	% Change
(M_c)	33	0	3.5	0	6.0	0
$M_{(10\%\ B)}$	38	15.0	4.0	14.5	6.2	3.4
$M_{(50\%\ B)}$	41	24.0	4.5	28.5	7.0	16.7
$M_{(100\%\ B)}$	34	3.0	4.2	20.0	6.8	13.4
$M_{(10\%\ R)}$	37	13.0	4.0	14.3	6.3	5.0
$M_{(50\%\ R)}$	43	30.0	4.5	28.7	7.5	25.0
$M_{(100\%\ R)}$	34	3.0	4.3	23.0	7.0	16.7
$M_{(50\%\ B+50\%R)}$	44	33.4	4.7	34.5	7.8	30.0

3.1. Compressive strength of concrete mixes

The compressive strength results in Table 7 are plotted in Fig. 4, which show that there was an increase in the compressive strength of the specimens when crushed bricks were used to replace the fine aggregates at all percentages below 100% replacement. Moreover, the maximum increase in strength was 23% corresponding to 50% replacement ratio.

When the fine aggregates were totally replaced by crushed bricks (100% replacement), the results showed a slight change in the compressive strength. The increasing in strength is in agreement with the results of previous researches reported in the literature. According to the research of Rashid et al. (2020) and Azunna et al. (2021), the increasing of compressive strength could be referred to the pozzolanic reactivity of the bricks; the $Ca(OH)_2$ crystals in concrete were consumed to generate calcium silicate hydrate (CSH), resulting in enhancing adhesion between the crushed bricks as a fine aggregates and the cement paste.

It can be seen from Table 7 and Fig. 5 that concrete mixes containing different percentages of recycled crushed concrete as a partial replacement of natural coarse aggregates content shows a similar trend but with higher values compared to those of crushed bricks. It is observed that when coarse aggregates were replaced by 50% with crushed concrete, the compressive strength at 7, 28 and 56 days were 30, 43, and 44 MPa, respectively, which represent the highest values of compressive strength. These results could be due to the well preparation of crushed recycled coarse aggregates (CRA); optimal gradation of RCA, shape and texture of RCA, and the quality of RCA that greatly influence the properties of produced concrete. The valuable matter is that the combination of the two types of substitutions maintained the positive effect of them on the compressive strength ($M_{50\% B,R}$).

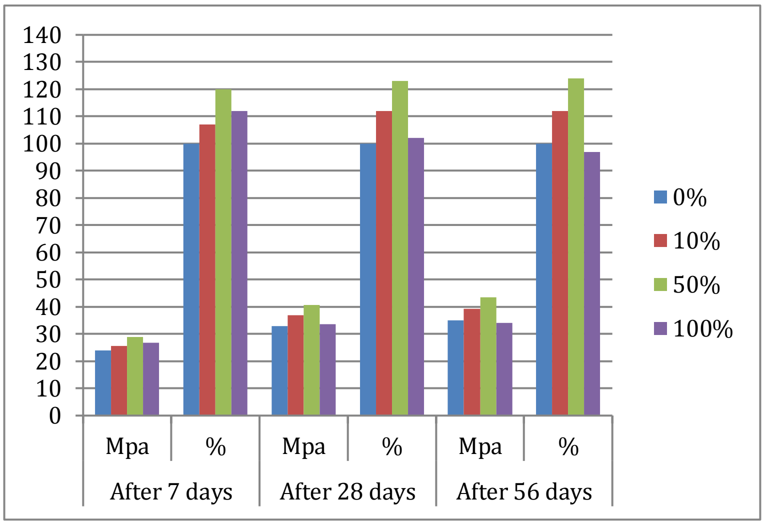

Fig. 4. Results of the compression test for the CB specimens.

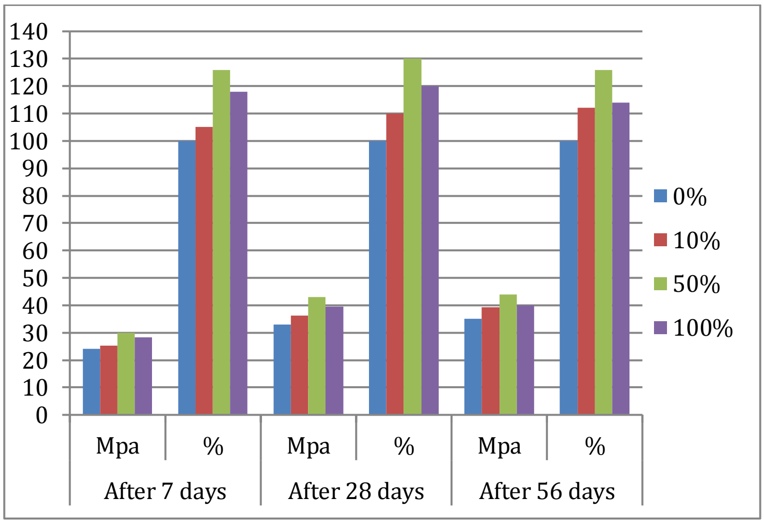

Fig. 5. Results of the compression test for the CRC specimens.

It is also observed that the superior results related to the strength gain were those of $M_{(50\% B,R)}$, the mix that incorporating the both types of aggregates alternatives.

It is worthy to study the effect of incorporating CB, and CRC as partial substitutions of fine or coarse aggregates in concrete mixes on compressive strength gain. Therefore, Fig. 6 is plotted to indicate the values of compressive strengths results through 7, 28, 56 days ages of concrete samples. It was found that the rate of compressive strength increased from 7 days until 28 days for all concrete mixes by almost 40%. In addition, the progression of strength continued after 28 days age but with a little increase as the usual of traditional concrete strength gain, meanwhile that CB and CRC maintained the rate of strength gain of concrete even after the standard age (28 days).

3.2. Splitting tensile strength of concrete mixes

The results of splitting tensile strength for all mixes are plotted in Fig. 7. It was observed that when fine aggregate is replaced by 50% crushed bricks, the tensile splitting strength at 28 days age was found to be the greatest value to record 28% increase compared to control mix. For the mixes where coarse aggregate is replaced with a percentage of crushed concrete, the increase in splitting tensile strength was 25% at 50% replacement ratio.

Fig. 8 shows a comparison for the average values of flexural strength of specimens with different percentages of brick-fine aggregate replacements, and CRC – coarse aggregate replacements. Flexure test results for the various concrete specimens are nearly showing similar trends as shown by the splitting tensile strength and compressive strength test results.

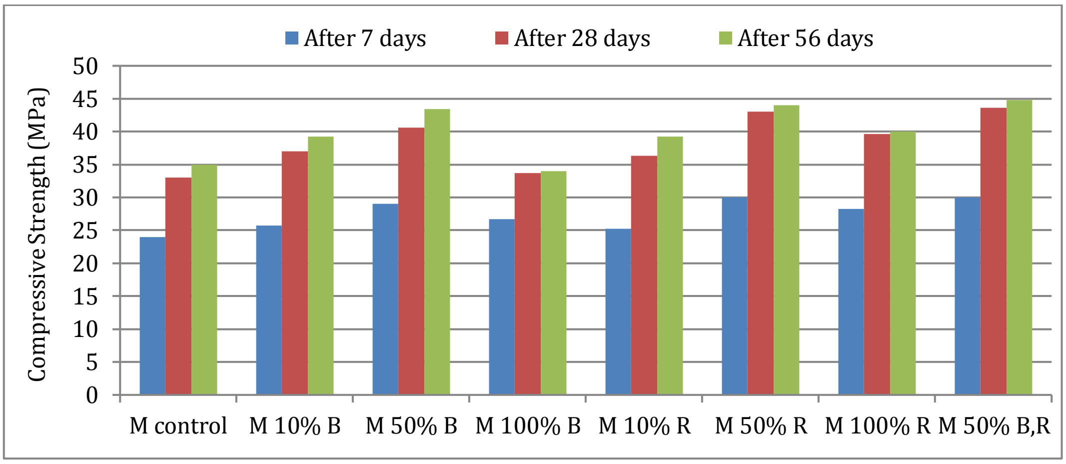

Fig. 6. Effect of the various percentages of CB & CRC on the compressive strength gain.

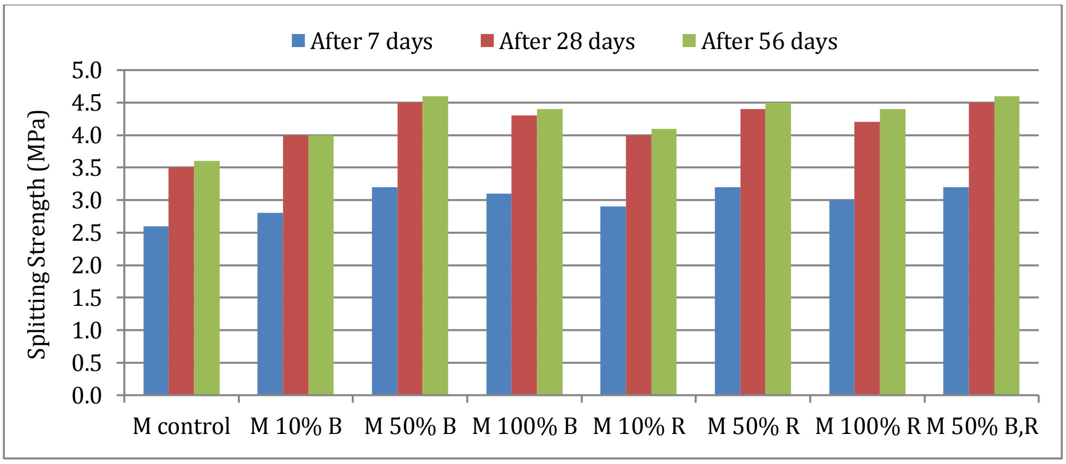

Fig. 7. Effect of the various percentages of CB & CRC on the splitting tensile strength gain.

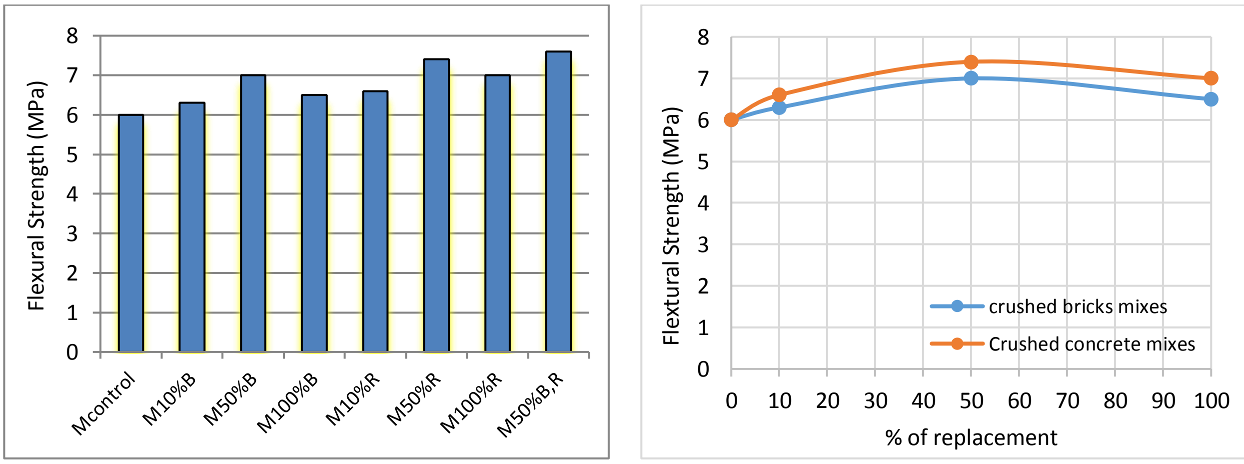

Fig. 8. Flexural strength of concrete mixes after 28 days.

4. Conclusions

Recycled materials were used to preserve the natural materials to produce sustainable concrete. Crushed brick was used to replace the natural fine aggregate and crushed recycled concrete was used to replace the natural coarse aggregate. Different percentages of the replacing materials were considered, namely: 0%, 10%, 50%, and 100%. The effect of the different percentages on the mechanical properties of the produced sustainable concrete was experimentally investigated. Based on the results of the current research the following conclusions could be drawn:

- Wastes such as bricks and concrete can be used as a partial replacement of fine and coarse aggregates in concrete as there was an overall improvement in compressive, tensile and flexural strengths in the mixture with these wastes.

- There is an optimum percentage of replacement that gives the highest effect when substituting fine aggregate with crushed bricks which was found to be 50 % in concrete.
- There is an optimum percentage of replacement that gives the highest effect when substituting coarse aggregate with crushed concrete which was found to be 50 % in concrete.
- At the suggested optimal ratio 50% of fine aggregate with crushed bricks, an increase of 23%, 28%, and 19% was obtained in the compressive, tensile, and flexural strengths, respectively relative to the control specimen.
- At the suggested optimal ratio 50% of coarse aggregate with crushed recycled concrete an increase of 30%, 25%, and 23% was achieved in the compressive, tensile, and flexural strengths, respectively relative to the control specimen.
- The most effective mix was at 50% replacement ratio of coarse aggregate with crushed recycled concrete in combination with 50% replacement ratio of fine aggregate with crushed bricks. The results of this mix showed 32%, 28%, 26% increase in compressive, tensile, and flexural strengths, respectively.

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Conflict of Interest

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