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RESEARCH

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Mechanical Properties and Flexural Strength of Reinforced Concrete Beams Containing Waste Material as Partial Replacement for Coarse Aggregates

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Abstract

The volume of waste materials and by products are increasing and endangering the environment safety. Some of these waste materials can be used in the production of building materials, such as concrete. In order to study the possibility of using some waste materials as aggregate replacement for the purpose of producing structural RC members this investigation was carried out. This research describes the results of test of reinforced concrete beams containing different types of waste materials, namely crumbed rubber, granular plastic, and crushed bricks. Ten RC beams containing different percentages (0%, 5%, 10%, and 15%) of waste materials as coarse aggregate replacement have been investigated. The beams were 150 × 200 mm in size and 2000 mm in length and tested under four points loading. Mechanical properties of the concrete used for the beams were also studied. Test results indicated a reduction in compressive strength, splitting tensile strength, and elastic modulus due to the inclusion of the waste materials used. The maximum loss in concrete compressive strength was recorded to be 54.95%, 50.31%, and 20.41% for concrete mix with 15% crumbed rubber, plastic waste aggregate, and 5% crushed brick, respectively. Test results of the beams showed that ultimate load capacity was reduced by 30.21% and 9.94% when 15% of crumbed rubber and granular plastic were used, respectively. The failure mode of all the tested beams was similar and followed same pattern, steel yielding followed by concrete compression failure. Finally, based on the flexural capacity of the beams tested it is recommend that gravel replacement of up to 15% of crumbed rubber, granular plastic, and crushed brick can be safely used to produce normal type of RC beams for minor structural application.

Keywords: waste material, rubber, plastic, broken brick, RC beams

1 Introduction

Waste materials specifically plastic and rubber wastes represent a main environmental issue of increasing hazards. Growing construction sector and demolition of buildings lead also to huge quantities of waste causing a serious environmental issue. Producing concrete containing waste materials seems to be a good partial solution to reduce the effect of this environmental issue. Many researchers have used waste materials in concrete mostly as partial replacement for the fine or coarse aggregate depending on the type or size of the waste material used. Here, some of those who have investigated the mechanical properties of the produced concrete will be reviewed, but the main focus will be on the studies investigating the structural applications of concrete containing waste materials.

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Sandanayake et. al. (2020) and Ahmad et. al. (2021) have made extensive review of different waste material utilization in concrete such as plastic, glass, rubber, fly ash, slag and demolition wastes and their mechanical properties. Aiello and Leuzzi (2010) utilized tyre shreds to replace both fine and coarse aggregates; they found out that the dimensions of the rubber particles have a major role on the strength of concrete. Compressive strength falls much more when replacing coarse aggregates compared with compressive strength loss of concretes when fine aggregates used.

Snelson et. al. (2009) replaced different percentage of aggregate reporting also a reduction in compressive strength and modulus of elasticity. Atef et al. (2021) used rubber powder replacing cement partially in concrete for various purposes and it was found that strength decreases with the inclusion of rubber powder, however they have recommended its use for hollow or solid construction blocks. Amiri et. al. (2021) studied the effect of adding combined rubber powder and recycled aggregate on mechanical properties and durability of concrete using different percentage of rubber powder up to 5% and recycled concrete aggregate up to 50%. They found that strength decreased with the increase of waste replacement, however increasing the WRP rates reduced the migration rate of chloride ions. Wang (2019) investigating rubberized concrete under confined and non-confined condition concluded that strength of concrete is significantly reduced with high replacement rubber aggregate; however the deformability is greatly enhanced. Reduction in strength of rubberized concrete is expected and can be attributed to the low compressive strength of rubber particles compared to normal aggregate and to the low adherence between cement paste and rubber particles.

Rahmani et. al. (2013), and Saikia and Brito (2014) studied the effect of partial replacement of fine aggregate with PET particles at different percentages. Results showed that the compressive strength of concrete increased at low percentage of replacement, however with additional increase in PET particles up to 10% and 15% the compressive strength of concrete reduced because of weak cohesion between the concrete mixture and the PET particles. Also the tensile strength decreased because the free water at the surface of plastic aggregate and smooth surface of the plastic particles can result in a weaker bond between these plastic pieces and the cement paste. Keihani et. al. (2019) studied polypropylene as aggregate replacement to produce medium strength concrete, they found that the workability of the mixes is reduced and the strength is reduced, however the normal 25 MPa strength can be achieved. Abu-Saleem et. al. (2021) investigated the effect of incorporating different combination of mixed types of recycled plastics on the strength performance of concrete, results indicated that increasing the plastic replacement ratio is more influential than the plastic type used.

Baciu et. al. (2022) added plastic wastes as dispersed fibers and found that concrete reinforced with PET fibers enhance mechanical properties of the concrete. Ikechunwu and Shabangu (2021) have combined crushed glass and melted PET plastic to produce masonry bricks and have found that a satisfactory construction brick can be produced using mix ratio of 70%:30% and 60%:40% of crushed glass to scrap plastic. Cachim (2009) studied the mechanical properties of brick aggregate concrete made with two types of bricks with different strength with different percentages of replacement. Results implied that concrete made with bricks of lower strength gives lower compressive strength, however, no reduction in the compressive strength was observed with 15% of aggregate replacement. Zhang and Zong (2014) test results with recycled brick as coarse aggregate showed that the compressive strength decreases as the replacement percentage increased up to 30%. However, all specimens showed good workability up to 40% waste replacement. This can be attributed to the increased absorption of recycled aggregate hence increased need to water as compared with conventional concrete. Uddin et. al. (2017) studied the effect of maximum size of crushed brick aggregate on the mechanical properties of hardened concrete. Results indicated that for higher content of cement smaller size gives higher compressive strength. Zeghad et. al. (2017) used refractory brick powder as a supplementary cementitious material to produce UHPC, the concrete produced was in the range of 82 to120 MPa. Wichrowska et. al. (2022) used different recycled wastes in concrete namely recycled coarse aggregate, recycled cement mortar, and fly ash slag mix. Results showed increase in concrete strength for 30% replacement and improved frost resistance.

The issue of structural behavior of members made from concrete containing different types of wastes has not been given much attention and researches in this subject are limited. Only a few studies have been conducted on the use of waste material in reinforced concrete beams compared to the studies available about their mechanical properties.

Ismail and Hassan (2016) tested twelve full-scale vibrated and self-consolidated rubberized concrete beams in order to study the effect of crumb rubber on flexural behavior, ductility, stiffness, and cracking pattern under flexural load. They reported that adding crumbed rubber to concrete limited the flexural crack width with slightly higher number of cracks as compared with conventional beam. Although the flexural capacity of rubberized reinforced concrete beams slightly decreased by the addition of crumbed rubber up to 20%, on the other hand, it improved the deformation capacity of the beams causing more ductile behavior.

Results of Mendis et. al. (2017) tests of reinforced rubberized concrete beams showed that rubber content had little effect on the ultimate flexural capacity of the beams and had minimal effect on the crack depth and spacing. In a study carried out by Hassanli et. al. (2017) four (CRC) beams and four (CRC) columns were cast by replacing (0%, 6%, 12%, and 18%) by volume of the fine aggregate with rubber. Results showed that the reduction in the flexural capacities of the tested rubberized reinforced beams and columns were only about 6% and 12%, respectively. Nabilah et. al. (2019) tested three full-scale RC beams with partial replacement of fine aggregate with crumbed rubber. Results revealed that the addition of crumbed rubber had only small effect on the flexural capacity of the tested beams. Also the use of rubber particles showed improvement in the deformation capacity under bending because of energy absorption property of rubber and larger deformability as compared with natural aggregate.

Mohammed (2017) studied the flexural behavior of two groups of reinforced concrete beams containing well graded PET waste shredded particles with three different sizes at proportion up to 15% to partially replace fine aggregate. Results showed that the beams containing square shredded PET plastic waste behaved like the control beam, also mode of failure and stiffness were not changed by adding PET waste. However, by the addition of plastic the ultimate load capacity decreased about 14.9% at 15% of PET waste content. Kim et. al. (2010) studied the structural performance of reinforced concrete beams containing recycled PET fiber, Short fibers made from PET were used with different volume fractions. Results showed that the PET fibers delayed the occurrence of cracks; also the ductility and ultimate strength were higher than the control beam. Akinyele and Ajede (2018) tested reinforced concrete beams with granulated plastic waste, they confirmed also similar results, lower moment capacity and wider cracks. Mohammed et. al. (2017) tested 24 beams to study the effect of incorporating recycled brick aggregates on the flexural behavior of reinforced concrete beams and compared the results with virgin brick aggregate. The results showed that there is no significant difference between load–displacement of both type of bricks, using recycled brick aggregate do not reduce the cracking moment and ultimate moment capacity. Rasheed and Salih (2019) tested reinforced beams made with crushed clay brick aggregates as coarse aggregate. Results showed that ultimate load capacity decreased by 5%. Ductility and toughness were less as compared with conventional beams. The number of cracks increased and their width became wider.

Literature search indicate that research on the mechanical properties of concrete containing waste material are too many, however research on the structural behavior and strength of members made from concrete containing different types of waste materials is limited. For the purpose of adding more information about the structural application of concrete containing different types of waste materials this investigation was carried out.

1.1 Research Significance

Large amount of waste materials may be used in construction hence the environment can be cleaned from large amount of these wastes. New types of concrete can be produced by incorporating waste materials, which tend to be lighter in weight, and may be used as structural elements in some type of precast concrete units for structural applications.

2 Experimental Program

The experimental work consists of testing 9 reinforced concrete beams containing different percentage of waste materials (Rubber, plastic, and crushed brick) and one control beam. The beam specimens were denoted as B_0 refers to control mix, R, P, B, refer to rubber, plastic and crushed bricks, respectively. The number subscripts (5, 10, and 15) refer to the aggregate replacement percentages. The control mix consisted of 490, 980, 735, and 207 kg for cement, coarse aggregate, fine aggregate, and water, respectively. In all mixes no changes is made for cement, fine aggregate, and water contents, only the coarse aggregate is partially replaced with the waste material. That is 5, 10, and 15% of the 980 kg of the coarse aggregate.

2.1 Materials

Ordinary Portland cement was used for all concrete mixes. Clean Natural River sand was used as fine aggregate. Crushed gravel with maximum size of 9.5 mm was used as coarse aggregate, both aggregate types gradations conform to ASTM C33 (2016) standard specification.

10 mm diameter steel bars with fy = 421 MPa and fu = 623MP [average of 3 bars] were used as main reinforcement for flexural at the bottom and top of the beams, and Φ8mm diameter steel bars with fy = 357 MPa and fu = 547 MPa were used for shear reinforcement. Old rubber sheets were collected from a cement factory where the plates were used as a conveyor belt for cement bags. The sheets were cut in to longitudinal strips then cut into small pieces of two different sizes namely 9.5 mm and 14 mm by means of a cutter as shown in Fig. 1. Plastic garbage container were collected from different dump

Fig. 1 Rubber particles.

Fig. 3 Crushed brick particles.

sites and used to produce granulated plastic aggregate. Garbage containers were subjected to crushing process by means of chipping machine in a plastic recycling plant in order to obtain plastic particles of the same shape and size of coarse aggregate as shown in Fig. 2.

New clay bricks of size (235 × 111 × 74) mm with an average compressive strength of 35.8 MPa from a local Company were used as partial replacement for coarse aggregate. The bricks were crushed into small pieces of three different sizes namely 9.5 mm, 4.75 mm, and 2.36 mm by mean of hammer, as shown in Fig. 3, so that the brick particles is close to the shape and size of the crushed stone aggregate. Before using the crushed brick in concrete mix it was put in water and made saturated surface dry (SSD) by immersing the crushed bricks particles in water for 24 h and then surface dried from extra water. For casting beams wooden molds were used.

2.2 Mix Proportions

A mix of normal strength concrete with target compressive strength of 35 MPa was chosen. The mix proportion for the concrete was (1:1.5:2) by weight (cement:fine aggregate:coarse aggregate) and water/cement ratio was 0.42. The coarse aggregate, fine aggregate, and cement were mixed first, after that waste material particles were sprayed over the mix continuously till homogeneous mix was obtained then water was added and mixing continued until thoroughly mixed. Beside the control mix three different waste material (crumbed rubber, plastic waste, and crushed brick) with three different percentage for each type of waste (5, 10, 15) % as coarse aggregate replacement were used for producing different concrete mixes. The materials control tests (compressive strength, split tensile, and elastic modulus) for each mix were all performed on (100 × 200) mm cylinders, three identical specimens for each property were tested using a digital compression machine of 4000 kN capacity. Compressive strength tests was carried out according to ASTM C39 (2012), split tensile tests according to ASTM C496 (2011), and modulus of elasticity tests according to ASTM C469 (2014) standard specifications.

Fig. 2 Granular plastic particles.

2.3 Beam Details

Nine reinforced concrete beams divided into three groups in addition to one control beam were cast. Each group has identical material quantities except the type and percentage of waste materials used as coarse aggregate replacement. The beam cross section was 150 mm wide and 200 mm in depth, the overall length was 2000 mm. All the beams were designed to fail in flexure with steel ratio ρ equal to 0.0064 tension steel reinforcement. Top reinforcement was provided only at the shear span to hold the stirrups in place. Details of flexural and shear reinforcements, and test setup are shown in Figs. 4 and 5.

Each beam was tested on simple span two central point loads of with an effective load span of 1500 mm. Central deflection was measured using a dial gage under the center line of the beam. The compressive strain of

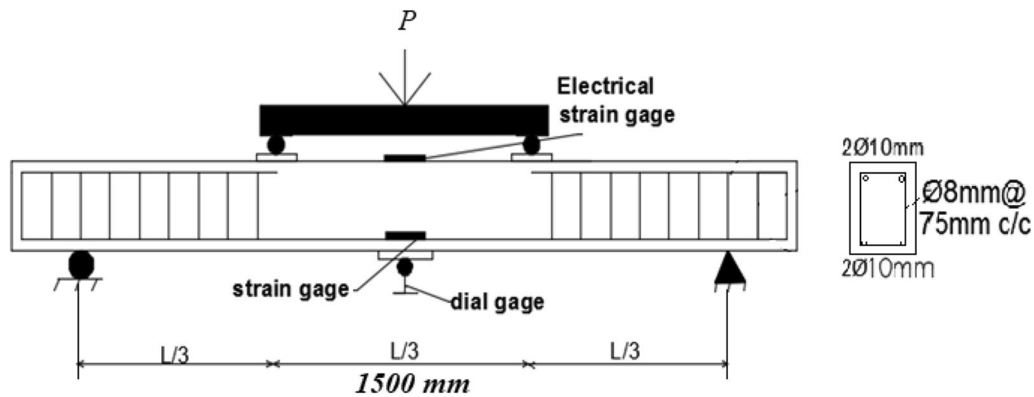

Fig. 4 Test setup and beam details.

Fig. 5 Beam under testing machine.

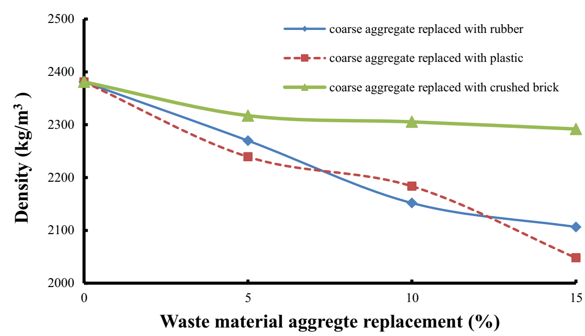

Fig. 6 Density of concrete with different types of waste material.

concrete and tensile strain in the steel were measured using electrical strain gages which were connected to a digital strain indictor instrument. For every 5 kN loading increment, strains and deflection were recorded. Progression of cracks under load was also monitored and marked on the beam.

3 Results and Discussion

3.1 Concrete Properties

3.1.1 Concrete Density

Test results of hardened concrete density containing different types of waste materials as compared with control specimens are shown in Fig. 6. A reduction in the density of concrete is observed with the incorporation of all types of waste materials used. This decrease can be attributed to the lower density of rubber particles, plastic particles, and brick particles as compared with natural aggregate. The maximum reductions in the density of concrete took place at 15% rubber, plastic, and brick aggregates which are 11.53%, 13.98%, and 3.74%, respectively. The reduction values in concrete density between concrete containing crumbed rubbers, granular plastic and crushed brick slightly differs for the same percentage of replacement. This is attributed to the difference in specific weight of the waste materials used.

3.1.2 Concrete Compressive Strength

Results of the compressive strength of concrete containing different types of waste materials and the control mix are given in Fig. 7. For concrete containing crumbed rubber and granular plastic waste material, a significant reduction in compressive strength with increasing of waste materials content is observed. The maximum reduction in the compressive strength for 15% waste content reached 54.95% for crumbed rubber, and 50.31% for plastic, however, concrete samples containing crushed brick as aggregate replacement show increment in compressive strength value as the replacement percentage increased. This behavior can be attributed to the high compressive strength of brick used (35 MPa) also the irregular shape and sharp edge of crushed brick particles which lead to higher bond between crushed brick particles and cement paste. In general, the strength loss can be attributed to the smooth surface of rubber waste material, low mechanical strength of rubber aggregate, the lack of good interlocking between the cement paste and

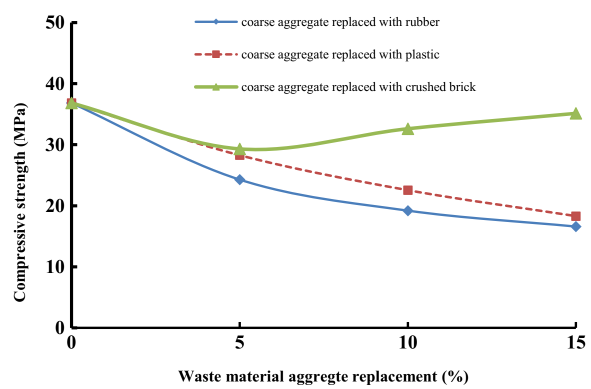

Fig. 7 Compressive strength of concrete with different types of waste material.

waste aggregates in addition to high deformation under load because of low elastic modulus of these materials as compared with natural aggregate. The high deformation taking place leads to a failure at a lower stress value compared with that of normal concrete. In concrete samples containing crumbed rubber and granular plastic cracks did not occur in the waste particles, but passed around the waste aggregates. This fact also indicates the poor bond strength between the cement paste and waste aggregates. In the case of control concrete and concrete samples containing crushed brick, the failure took place right through the aggregates, indicating higher bond strength between the cement paste and coarse aggregates.

3.1.3 Concrete Split Tensile Strength

Fig. 8 shows the effect of adding the waste materials on the split tensile strength of the concrete. The behavior is similar to the compressive strength, where a steady and continuous reduction in tensile strength were noticed, attributing this behavior to the same reasons such the particle size of waste aggregate, surface nature, and low adhesive strength between the surface of waste materials and the cement paste leading to low bond. The results indicated that regardless of the type of waste materials used for larger content of each type of waste material the reduction in tensile strength of concrete is increased. The maximum reduction took place at 15% replacement of crumbed rubber, plastic, and crushed brick which are 65%, 43.15%, and 13.59%, respectively. It was also noticed that the control specimens and crushed brick specimens had the brittle-type failure, sudden breakage accompanied by sound. On the other hand, for the specimens containing waste material aggregates, the failure occurred smoothly without any noise during breakage. It is also indicated that the addition of waste particles will induce ductility into the concrete specimens. Therefore, when added in proper proportion, the concrete can be made ductile with the addition of waste aggregates in concrete.

3.1.4 Concrete Modulus of Elasticity

Fig. 9 shows variation of the modulus of elasticity of concrete with the waste materials percentage. The data indicate a continuous decrease of elastic modulus with increase of the percentage of coarse aggregate replacement for both crumbed rubber and plastic waste materials while the elastic modulus value of concrete samples containing crushed brick aggregate increased as the replacement percent increased. This behavior can be attributed to the lower elastic modulus of rubber and plastic waste material aggregates as compared to that of natural and brick aggregate. Also, test results showed that the replacement of coarse aggregate with crumbed rubber particles had more effect on the reduction of elastic modulus than plastic for the same percentage. This occurred because of the fact that crumbed rubber

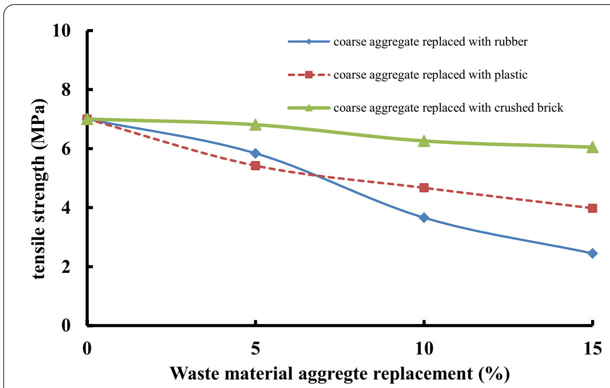

Fig. 8 Splitting tensile strength of concrete with different types of waste material.

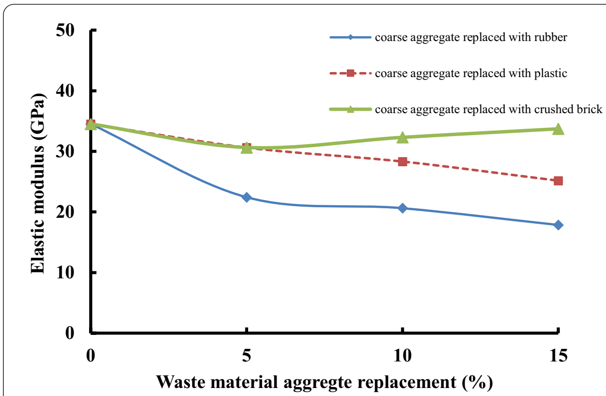

Fig. 9 Elastic modulus of concrete with different types of waste material.

particles will suffer from higher deformation under compressive stress due to their bigger size as compared with two other types of waste material, also due to the possibility of more segregation due to high concentration of rubber aggregates at the surface of the specimens. Taking care of aggregate particles arrangement is important with regard to the elastic modulus because the deformation of waste particles under stress has great effect on the elastic modulus. On the other hand, concrete elastic modulus of specimens containing crushed brick increase as the replacement percentage increased due to their stronger particles as compared to rubber and plastic waste particles. However a reduction in the elastic modulus was observed by others (Cachim, 2009; Uddin et al., 2017; Zhang & Zong, 2014). This contradiction is probably due to the type and size of the crushed bricks used. Larger waste brick particles and weaker bricks can produce weaker concrete with reduced modulus of elasticity. Compressive stress–strain relationships of the tested concretes with waste replacements showed similar characteristics with slight differences in the slope of the curves depending on the replacement ratios of the waste material. With more replacement ratio, the slope of the curves decreased and with decreased failure strength indicating less toughness. This behavior will be more discussed for the load deflection curves of the beams tested.

3.2 Tested Beams

3.2.1 Cracking and Ultimate Loads

Results of the first cracking and failure loads of the beams containing 0%, 5%, 10%, and 15% of the waste materials are presented in Table 1. There is no clear pattern relating the first cracking loads to the percentage of waste replacement and the control beam. For both rubberized beams containing 5%, and 10% waste material, first crack formed at 15 kN, which is the same for control beam and the load decreased to 10 kN as the replacement percentage increased to 15%. However, the variation in the failure loads is indicative. For the beams with rubber waste content the reductions in failure load are 10.78%, 19.77%, and 30.21% for 5%, 10% and 15% rubber content, respectively. These reductions are lower as compared with the reduction in the compressive strength value of their cylinder compressive strength tests. This behavior was also noticed by Ismail and Hassan (2016), Mendis et. al. (2017), and Nabilah et al. (2019) for rubberized concrete. For beams with plastic waste content the reductions in the flexure load capacity are 5.51%, 7.25%, and 9.94% for 5%, 10%, and 15% of granular plastic content, respectively. Reduction in load capacity up to 15% granular plastic waste content is not high, indicating that in tension controlled concrete members the moderate change of compressive strength has no significant effect of the load capacity. Accordingly, reinforced concrete beams containing plastic waste particles up to 15% behave like normal concrete beam. Same behavior was observed by Mohammed (2017), and Akinyele and Ajede (2018) for beams with plastic wastes. Finally, for the beams with broken brick content the value of ultimate load increased by 5.75%, 8.76%, and 0.44% for 5%, 10%, and 15% crushed brick content, respectively. The increment is not that significant and it decreases at higher rate of replacement, but it is still slightly higher than control beam. This behavior was attributed to the higher compressive strength of the brick used 35 MPa, also the irregular shape and sharp edge of brick particles which lead to higher bond between crushed brick and cement paste. From results, it can be observed that large variation in waste materials content within the limits of this study had little effect on the ultimate flexural capacity of the beams.

Table 1 Load-carrying capacity of the beams.

Beam	First cracking load (kN)	Failure load (kN)	Decrease in failure load (%)
B_0	15	53.49	–
R_5	15	47.72	10.78
R_{10}	15	42.91	19.77
R_{15}	10	37.33	30.21
P_5	14	50.54	5.51
P_{10}	15	49.61	7.25
P_{15}	10	48.17	9.94
B_5	18.8	56.57	5.75
B_{10}	19	58.18	8.76
B_{15}	16	53.73	0.44

3.2.2 Load–Deflection Relationship

The load–deflection values were measured for the beams up to 40 mm displacement at mid-span although some of the beams would have sustained slightly more deflection but with descended load. The load–deflection curves for beams with different replacement ratios for rubber, plastic, and crushed bricks along with the control beam are shown in Figs. 10, 11, and 12, respectively. In general, all the beams followed a similar pattern, a linear portion for the first part of the loading until the appearance and propagation of cracks, then a smooth change of slope till the failure of the beam. The stiffness (p/δ) of the control beam is higher than all other beams. The stiffness decreases with the increase of the percentage of the waste material replacement.

In general, it can be concluded that inclusion of waste material has some effect to reduce or improve deflection

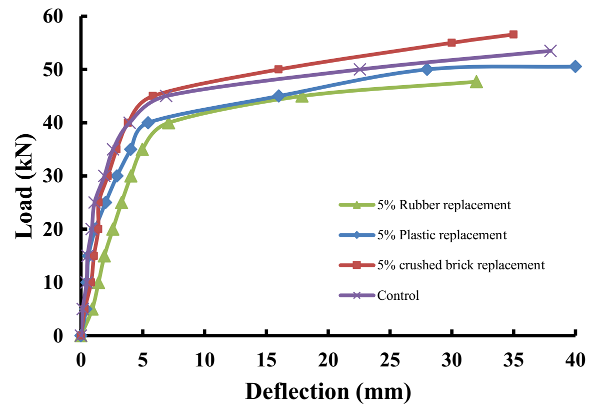

Fig. 10 Load–deflection for beams containing 5% of waste materials.

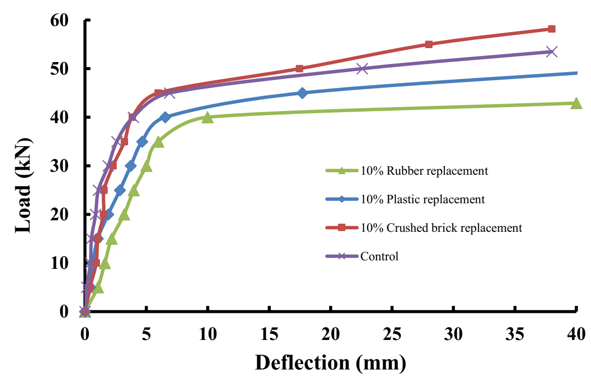

Fig. 11 Load–deflection for beams containing 10% of waste materials.

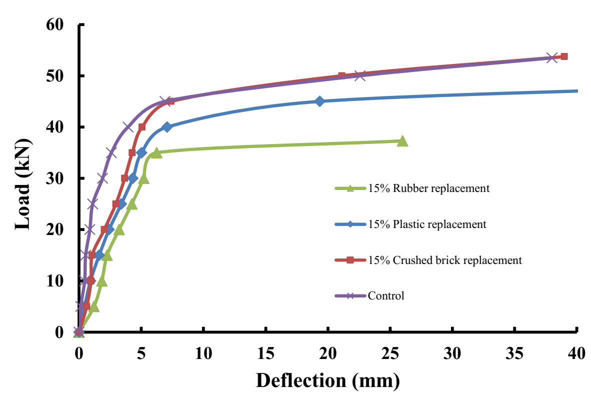

Fig. 12 Load–deflection for beams containing 15% of waste materials.

values as compared with control reinforced beam according to the type of waste used. For the purpose of comparison between the waste materials, Figs. 13, 14, and 15

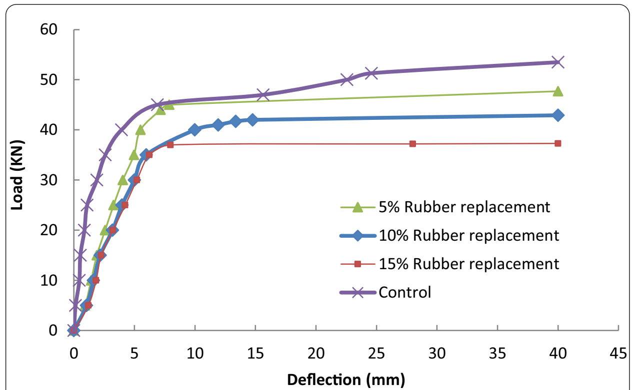

Fig. 13 Load–deflection for beams with crumbed rubber waste.

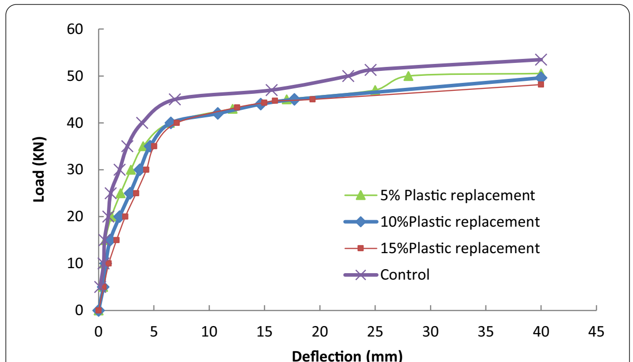

Fig. 14 Load–deflection for beams with granular plastic waste.

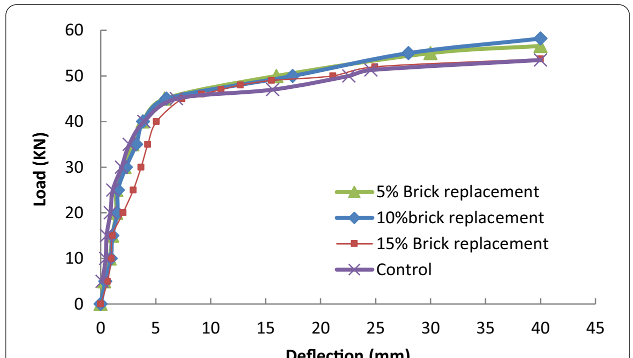

Fig. 15 Load–deflection for beams containing crushed brick.

show the load deflection curves for the beams with the same replacement ratio for the three waste materials containing 5%, 10%, and 15% replacement, respectively. The beams with rubber and plastic waste deflected more under the same level of loading as compared with beams containing crushed brick and control beam. This behavior can be attributed to the high deformation under load and energy absorption property of rubber and plastic waste as compared with natural aggregate. Maximum deflection for all concrete beams with waste materials are nearly the same and differ slightly from that of control beam except of the beam containing high rubber particles where the inclusion of rubber have significant effect on the deflection at ultimate loads.

3.2.3 Cracking and Failure Pattern

The appearances of reinforced concrete elements may greatly be detracted if cracks develop and more so when cracks are prominent. Excessive cracks and deep cracks affect the durability of concrete. It was observed in all beams that flexural cracks started first in the bending region and propagated vertically upwards. Subsequent cracks propagated away from the two points loaded area. Figs. 16, 17, and 18 show the crack development of the beams containing crumbed rubber, granular plastic, and crushed brick, respectively, the figures include also the control beam after failure. From cracking patterns of the beams it is observed that the inclusion of different types of waste materials in the beams has no significant effect on the cracks pattern and their progress. The number and extent of cracks were very similar. The crack patterns and failure mode of all tested beams show typical flexural failure mode; no shear failure was observed as the beams were provided with the required stirrups. Failure of all the beams (except for R_{10} in which concrete compression failure preceded) started by the yielding of steel followed by concrete compression failure as it is clear from the beam pictures after testing in Figs. 16, 17 and 18, and the values of strains measured. No clear conclusion can be drawn regarding the differences between number, width and length of cracks developed in the beams with waste materials compared to the control beam. In general, similar to the other properties of beams containing waste particles, cracking pattern behaves similar to that of normal reinforced concrete beams.

3.2.4 Concrete and Steel Strains

Concrete strain was measured at the top fiber of the beams at mid-span. Table 2 shows concrete and steel strains at failure load. Comparing the maximum compressive strain from specimens containing different types of waste materials as compared with control beam, results indicate that for all the beams the maximum compressive strain increased as the replacement percentage increase. On the other hand, the maximum strain of concrete containing crushed brick decreased up to 10% replacement percentage then continues to increase up to 15%. In all the beams except R_{10}, concrete strain has reached failure value after yielding of steel. However, in beam R_{10} with 10% rubber replacement the concrete strain has exceeded failure value while steel strain is below yield value which indicated concrete compression

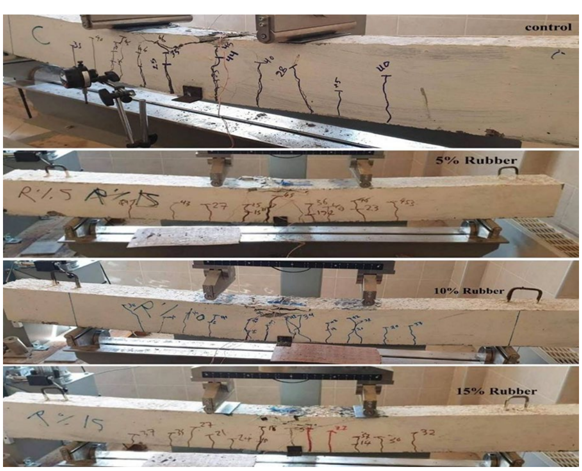

Fig. 16 Failure mode of beams containing crumbed rubber.

Fig. 17 Failure mode of beams containing granular plastic.

Fig. 18 Failure mode of beams containing crushed brick.

Table 2 Measured concrete and steel strain at failure.

Beam specimen	Failure load (kN)	Steel strain (micro)	Concrete strain (micro)
B_0	53.49	3562	3212
R_5	47.72	2434	3402
R_{10}	42.91	1329	5231
R_{15}	37.33	2264	4816
P_5	50.54	3331	4103
P_{10}	49.61	2631	4187
P_{15}	48.17	2274	4257
B_5	56.57	4196	3554
B_{10}	58.18	4473	3512
B_{15}	53.73	4623	3534

Table 3 Toughness and ductility factors of the beams.

Beam	Toughness (kN mm)	Ductility factor	Ductility ratio
B_0	1883	10.2	1
R_5	1701	8.0	0.78
R_{10}	1528	7.7	0.75
R_{15}	1366	8.3	0.81
P_5	1751	7.4	0.73
P_{10}	1700	7.2	0.71
P_{15}	1667	6.9	0.68
B_5	1955	8.3	0.81
B_{10}	1957	7.4	0.73
B_{15}	1863	7.6	0.75

failure as mentioned before. From the strain values, it can be observed that the deformability of the beams containing crumbed rubber and granular plastic particles played a role in strain values. More deformability leads to more strain values, and the capability for continued deformation under decreased load. It was also observed that all beams reached the crushed strain except the beam containing 5% crumbed rubber. The reading from strain gages indicated also that yielding occurred in the control beam and the beams containing different percentage of plastic waste material and crushed brick specimens prior to the concrete crushing of the beam, while the beam containing 10% rubber failed by compression of concrete and the steel stain is below yield value. Comparing the maximum yielding strain, the maximum strain of the reinforcement increased as the replacement percentage increased for specimens containing granular plastic waste aggregate and crushed brick aggregate.

3.2.5 Toughness and Ductility of the Beams

From the load deflection curves of in Figs. 10, 11, and 12, the toughness of the beams (area under load–deflection curve up to max 40 mm deflection—as an energy absorption measure) is calculated and shown in Table 3. Results indicate that the toughness of the control beam is more than all others except for the crushed brick beams which are slightly above the control beam value. The value of toughness of the beams containing waste replacement decreases as the waste content increases. The decrease rate is more for beams with rubber replacement, less decrease rate for plastic waste, and no significant decrease for brick waste beams. Hence in terms of energy absorption property, within the limits of these tests no benefit is gained from replacing aggregate by rubber or plastic wastes. Ductility factor is defined as the ratio of the displacement at first yield to the displacement at failure. It is very difficult to specify exactly the first yield deflection in a concrete beam, therefore the deflection at 75% of the failure load as adopted by Pam et al. (2001) is considered, and the 40 mm deflection is taken as the failure deflection. Results of the ductility factors are shown in Table 3 along with ductility ratio which the value of ductility factor of the beams divided by the ductility factor of the control beam. The results show that all the beams possess less ductility compared to the control beam, and all about 25% less. The higher value of the control beam is due to its higher stiffness before yielding and adapting 75% of the failure load as base for yielding gives small value for the deflection.

4 Analysis of the Beams

For the analysis of a reinforced concrete beam, strain and stress distribution at ultimate stage of loading is required. Total compressive forces acting on the section depends on the compressive strength of the material. The depth of the compression block varies with the variation of material compressive strength. Similarly, from the strain compatibility the steel reinforcement strain will be influenced by the strain values of concrete material at or close to failure. Detailed study of stress–strain behavior of concrete with replaced aggregate of up to 40% with rubber particles (Strukar et al., 2018) have shown concrete strain up to 8000 micro for high content rubber percentages. Concretes with plastic contents up to 45% have also shown high strain close to failure (4500 micro) (Abu-Saleem et al., 2021; Xuan et al., 2017).

Strain measurements of the tested beams have generally shown similar patterns, and have all initiated failure by yielding of steel reinforcement [under reinforced] except R_{10} concrete compression failure was initiated. Therefore, it seems reasonable for the analysis of beams containing waste materials to follow the same procedure and assumptions for normal strength concrete in accordance to ACI 318 (2019).

The stress and strain distribution as shown in Fig. 19 is assumed, and tensile failure will occur. Further tests and future studies may show the invalidity of the normal concrete stress–strain distributions, and modifications to be made as the results of this analysis may show. The moment capacity of the section is calculated following these steps:

a. Calculate [a] the depth of the compression block from Eq. (1) derived from equilibrium of forces acting on the section. The values are shown in Table 4:

$$a = \frac{\rho \text{fy}\ d}{0.85\ \text{fc}'}, \tag{1}$$

where ρ is the steel ratio $\frac{As}{bd}$,

fy is steel yield strength, b = width of the beam, d = effective depth, fc′ = concrete compressive strength.

b. From the value of [a] calculate value of [c] depth of neutral axis using same value as suggested by ACI 318, $a = 0.85c$.

c. Check tension control failure mode. With known value of compression block depth [a] the strain in the steel is checked from the compatibility equation derived from the strain distribution diagram in Fig. 19. If the value of steel strain is above 0.005, then the yielding of reinforcement is assured (tensile flexural failure) and for a tension controlled beam the nominal moment capacity is calculated from Eq. (2):

Table 4 Test and calculated moment capacity of the beams.

Beam	[a] (mm)	Test moment (kN m)	Calculated moment (kN m)	Test/calculated
R_0	14.00	13.37	11.40	1.17
R_5	21.30	11.93	11.17	1.07
R_{10}	26.90	10.73	10.98	0.98
R_{15}	31.20	9.33	10.84	0.86
P_5	18.30	12.64	11.26	1.12
P_{10}	22.90	12.40	11.11	1.12
P_{15}	28.30	12.04	10.94	1.10
B_5	17.70	14.14	11.28	1.25
B_{10}	15.90	14.55	11.35	1.28
B_{15}	14.70	13.43	11.38	1.18

$$M = \text{As}\ \ \text{fy}\left(d - \frac{a}{2}\right). \tag{2}$$

d. If yielding of steel in not assured calculate the nominal moment capacity from Eq. (3):

$$M = 0.85\ \text{fc}'\ ab\left(d - \frac{a}{2}\right). \tag{3}$$

The values of the moment capacity of the beams are calculated and shown in Table 4. If εs ≥ 0.005 then tensile failure mode is assured.

Ratio of the test values to the calculated values indicate that the analysis under estimate the moment capacity of the beams even for the normal concrete beams as well as the brick beams which are very similar to the normal beams as far as the strength of the concrete concerned. Results being under-estimated are acceptable and

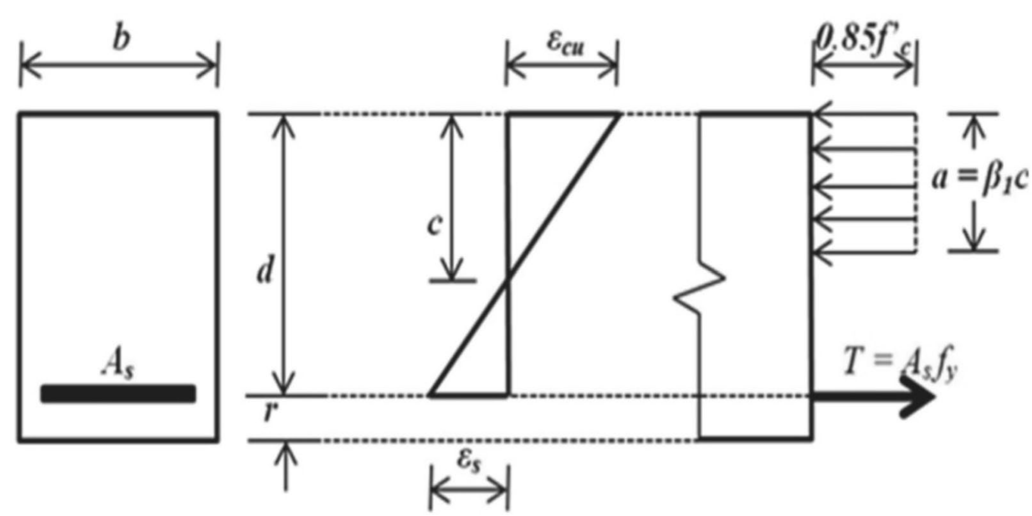

Fig. 19 Stress and strain distribution acting on RC beam section.

preferred for design purposes. However some correction values or factors to be applied may be reasonable taking into account the reduced strength of the waste material concrete or the enhanced deformability (increased strain at failure) of the concrete containing deformable waste materials especially rubber with high deformability, perhaps in the value of the $0.85fc'$ of the compression block in order to be reflected in the value of [a] which is the main factor in the calculation of the section moment capacity. More research is required in this area.

Based on these results in general it is rather acceptable to apply the simple ACI 318 Code analysis for the purpose of design of reinforced concrete beams containing waste materials described in this investigation.

5 Conclusions

From the results of the tested beams with (5%, 10%, and 15%) waste materials replacements, the following conclusions can be drawn:

1. The use of the waste material aggregates in the concrete reduced the overall concrete density when compared to conventional concrete which lead to produce medium weight concrete. The maximum reductions in density were; 11.53%, 13.98%, and 3.74% for 15% aggregate replacement of crumbed rubber, granular plastic, and crushed brick, respectively.
2. The compressive strength of the concrete was found to decrease by 54.95%, and 50.31% for 15% crumbed rubber and granular plastic replacements, respectively. However, the strength increased for the type of crushed brick used in this study as the percentage replacement increased.
3. The splitting tensile strength of concrete regardless of the type of waste materials replacement significantly decreases with increase in the percentage of waste materials content in the concrete. Reduction in splitting tensile strength was found to be 65.00%, 43.15%, and 13.59% at 15% replacement of crumbed rubber, granular plastic and crushed brick, respectively.
4. The elastic modulus of concrete made with rubber and plastic waste materials was found to decrease with increase in the percentage of waste particles. The elastic modulus decreased by 48.29%, and 27.14% for 15% crumbed rubber and granular plastic, respectively.
5. Ultimate load capacity for the beams tested was moderately reduced when crumbed rubber and granular plastic were used. Maximum reduction was found to be 30.21% and 9.94% for 15% crumbed rubber and granular plastic, respectively. On the other hand, the ultimate load capacity increased 8.76% for 10% brick replacement.
6. Cracking progress and pattern are not much changed when different types of waste material are used as compared with control beam. Stiffness of the beams was reduced when different types of waste material used in the concrete.
7. Introduction of waste material in concrete tends to reduce the toughness and ductility factors of the beams, however with deformable waste material the deformability of the beams increases before failure.
8. From the above finding, it can be concluded that an acceptable normal strength concrete can be produced by replacing coarse aggregate with up to 15% of waste materials and it is recommended that this type of waste material concrete may be used as structural members.

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Author contributions
The first author has carried out all the experimental work as part of her Master's degree. The second author has written this article abstracted from the thesis and has revised it. Both authors read and approved the final manuscript.

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