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Flexural behavior of sustainable reinforced concrete beams containing HDPE plastic waste as coarse aggregate

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Abstract: The peril increasing due to the increase in the accumulation of different types of plastic waste in the environment which is often burned, buried, or thrown into rivers and seas polluting the air, soil, and water. Therefore, it has become necessary to find ways to get rid of them primarily by using them as substitutes for materials used in other industries. Beams with 180 × 280 mm cross section and 2000 mm length were tested under a four-point bending load system. Three beams were ast with sustainable concrete made from high-strength concrete (HSC) containing high-density polyethylene (HDPE) plastic type was taken from shredding vegetable boxes and used as a substitute for coarse aggregate with 10%, 20%, and 30% ratios. The fourth one contains 0% HDPE replacement and represents the reference beam. Test results for the beam with 30% replacement showed that the cracking manner and failure time were close to the reference beam and the toughness increased by 24%, while the load carrying capacity was reduced by 7%. These results are very promising to take into consideration a partial HDPE plastic replacement of 30% by the natural coarse aggregate while keeping a competent structural flexural behavior.

Subjects: Concrete & Cement; Structural Engineering; Sustainability

Keywords: HDPE plastic waste; vegetable plastic boxes; coarse aggregate substitutes; sustainable concrete; high strength concrete; reinforced concrete beam; flexural behavior; ductility; stiffness; toughness

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PUBLIC INTEREST STATEMENT

The danger arising from the accumulation of industrial waste in the environment, especially waste that cannot be degradable over time, such as plastic, requires a serious search for safe ways to dispose of it. The safest and most intelligent of these methods is sustainability by making use of them as raw materials for other industries such as the concrete industry, either as a binder or as fine and coarse aggregate, thus preserving the natural resources that are usually used. This research focuses on using the plastic collected from plastic fruit boxes and used as an alternative to the gravel of nature that is used in concrete after shredding them in a way that simulates the original. Thus, the waste of these boxes is disposed of safely for a long time, and we preserve nature.

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2. Introduction
The demand for the different industrial materials required for daily needs has exponentially increased due to the quick enlargement of the global economy. This development in the manufacturing industry has two negative impacts on the environment. Firstly, the increase in the production industry means higher energy demand, which results in higher carbon dioxide emissions. For instance, each ton of plastic resin production and transportation is responsible for approximately 2.5 tons of emitted CO₂ into the atmosphere (Associates, 2011). Secondly, the produced materials are mostly used for a limited time, partially used, or disposable. Thus, the wastes of these materials need treatments and landfills, which again impact the treatment region’s environment (soil, water, and air). Sustainability has become the best way to reduce those two major negative impacts by using industrial production wastes as alternatives to the materials used in other industries, which contributes to protecting the environment and stopping the depletion of natural resources for those industries. Among the most widely produced materials for human daily life, use is plastic, where disposable products for various purposes are made of plastic (Webb et al., 2013). The production of plastic materials is returning to the early years of the 20th century, while since approximately 1960 it has been mass produced for many usages (Scalenghe, 2018). The yearly global production of plastic in 2015 reached approximately 400 million tons (Chamas et al., 2020). Plastic materials are known for their extremely long decomposition life that extends to more than 50 years (Müller et al., 2001) and may reach 1000 years if plastic is buried in landfills (Chamas et al., 2020; Delaney, 2013). Plastic single-use or limited-use containers are among the vastly daily used products. For instance, plastic boxes are mass produced for use as vegetable containers, which urges the waste management planners to encourage the recycling of these boxes as useful means to eliminate or reduce their environmental impact.

The increase of the environmental pollution by several industrial waste materials has been highlighted as an important issue around the world in the construction and building sector sustainability (M.F. Ahmed et al., 2022). With the rapid demand for daily human single-use plastics, and owing to its tough degradation resistance, the reuse of plastic waste in concrete construction was suggested by many previous scholars. These wastes were from different plastic sources that were made from different materials, and were utilized in different forms in concrete. The recycled plastic wastes were cut into fine slices for use as matrix fibers or shredded into graded pieces for use as fine or coarse aggregates. Several previous works (Pacheco-Torgal et al., 2012; Saikia & De Brito, 2012; Sharma & Bansal, 2016; Yin et al., 2015) were conducted to collect research literature on the use of plastic waste in the construction industry. However, the reviewed research focus was mainly on the reuse of polyethylene terephthalate (PET) in cement mortars and concrete (Ojeda, 2021). Rahmani et al. (Rahmani et al., 2013), Ismail and Al-Hashmi (Ismail & Al-Hashmi, 2008), and, Mohammed et al. (Mohammed et al., 2019) reported a slump decrease with the increase of the substitution percentage of plastic waste as a mixture aggregate. The slump decrease was related to the fluidity retardation due to the irregular or angular shape of the plastic waste particles. On the other hand, other previous researchers (Choi et al., 2009; Li & Kaewunruen, 2019; Senhadji et al., 2015) reported an increasing trend of the slump with the increase of the used percentage of plastic waste aggregates, which was attributed to the zero water absorption of plastic waste aggregates. Despite the disagreement about the effect of waste plastic aggregates on workability, many previous studies (Almeshal et al., 2020; Coppola et al., 2018; Ferreira et al., 2012; Hannawi et al., 2010; Mohammed et al., 2019; Safi et al., 2013; Saikia & De Brito, 2014) agreed that increasing its volume percentage reduces the density of concrete. Cordoba et al. (Ávila Cordoba et al., 2015) and Marzouk et al. (Marzouk et al., 2007) agreed that larger plastic aggregate particles result in lower compressive strength of concrete, while other researchers (Ferreira et al., 2012; Saikia & De Brito, 2014) reported opposite results. However, most of the related research (Gouasmi et al., 2019; Hameed & Ahmed, 2019; Jacob-Vaillancourt & Sorelli, 2018; Jain et al., 2019;
Khalil & Al Obeid, 2020; Khalil & Mahdi, 2020; Mercante et al., 2018; Mohammadinia et al., 2019; Mohammed et al., 2019) agreed that using plastic waste aggregates leads to a continuous reduction in compressive strength. Ojeda (Ojeda, 2021) suggested a multivariable formula that indicates a linear reduction of compressive strength with the increased plastic waste and water/cement ratio. As for the compressive strength, the vast of the available literature (Almeshal et al., 2020; Alqahtani & Zafar, 2021; Arivalagan, 2020; Jain et al., 2019; Khalil & Al Obeid, 2020; Mohammadinia et al., 2019; Mohammed et al., 2019; Park & Kim, 2020; Thornycroft et al., 2018; H. U. Ahmed et al., 2021) indicated that the splitting tensile strength, modulus of elasticity, and flexural strength of concrete decrease with the increase of aggregate replacement by plastic wastes. However, other research indicated the positive influence of recycled plastic aggregate on the abrasion resistance (Ferreira et al., 2012; Jain et al., 2019; Saikia & De Brito, 2014), impact strength (Saxena et al., 2018) of concrete, and shear resistance exposed to heating (Abdul-Razzaq, 2015).

Most of the reviewed research was directed to investigate the influence of plastic wastes as fine aggregates or as fibers. Fewer studies (Alqahtani et al., 2017; Fraj et al., 2010; Kan & Demirboga, 2009; Lima et al., 2010; Saikia & De Brito, 2013) explored the utilization of plastic wastes as coarse aggregate in concrete. Kan and Demirboga (Kan & Demirboga, 2009) investigated the influence of partial and full replacements (0, 25, 50, 75, and 100%) of natural fine and coarse aggregates by light-weight heat-treated expanded polystyrene foam particles (EPS). They reported a continuous decrease in density and compressive strength as the percentage of recycled plastic aggregate increased. However, they concluded that the obtained mixtures can be classified as semi-structural concrete based on the obtained strengths (12.6 to 23.3 MPa). Lima et al. (Lima et al., 2010) investigated the effect of utilizing recycled ethylene vinyl acetate (EVA) waste from the footwear industry as replacements of coarse aggregate in lightweight concrete. The recycled EVA was added in natural coarse aggregate replacement percentages of 0, 25, and 50% with or without similar percentage replacements of recycled concrete wastes. The results indicated reductions in density, compressive strength, splitting tensile strength, and flexural strength as the plastic waste percentage increased. However, an increase in the flexural toughness and ductility was reported owing to a significant development in the plastic behavior of concrete represented by noticeably higher displacements. Saikia and Bidro (Saikia & De Brito, 2013) investigated the potential of utilizing three types of recycled PET wastes as fine and coarse aggregates in concrete. They reported a significant decrease in compressive strength for mixtures including plastic waste aggregates, but a higher ratio of early age (0–7 days) strength to the corresponding three-months strength. They also reported a proportional decrease in the splitting tensile strength and flexural strength for plastic waste aggregate mixtures, while an increase in toughness was recorded compared to the reference mixture with conventional concrete. The increase in toughness was higher for specimens with larger recycled plastic aggregate particles. For similar mixtures, Ferreira et al. (Ferreira et al., 2012) reported drops in compressive strength, splitting tensile strength, and modulus of elasticity. Alqahtani et al. (Alqahtani et al., 2017) utilized manufactured plastic waste particles as replacements (0, 25, 50, 75, and 100%) of coarse aggregate in lightweight concrete. They indicated that the mixtures slump in addition to the compressive, splitting tensile and flexural strengths decreased with the increase of plastic aggregate replacements, while the post-peak deflection and hence the ductility exhibited a noticeable increase.

As discussed in the previous paragraphs, rich research literature is available and continues published on the mechanical properties and durability using material-scale tests. On the other hand, the structural performance of reinforced concrete beams incorporating plastic waste aggregates was also investigated by many previous researchers. Jawad et al. (Jawad et al., 2019) experimentally investigated the structural performance of pultruded glass-fiber polymer bars (GFRP) reinforced concrete beams incorporating recycled PET plastic waste powder. The results indicated that using PET powder could increase the compressive and tensile strength by more than 17%. The obtained flexural records from the four-point bending test indicated that using PET powder with GFRP bars exhibited better load capacity at cracking and failure with higher
deformations and cracking compared to the conventional steel bar-reinforced beams. Khatib et al. (Khatib et al., 2020) investigated the three-point bending performance of reinforced concrete beams incorporating fibers made from plastic waste straws. The results showed that the beams reinforced with 1.5 and 3.0% of the plastic waste straws retained approximately the same ultimate load as the reference beam without fibers. However, these beams tended to exhibit a more cracking and higher tensile strain, which increased their ductility compared to the reference beam. Adnan and Dawood (Adnan & Dawood, 2020) investigated the flexural behavior of reinforced normal concrete beams containing recycled PET plastic waste as synthetic fibers. Five beams of 1400 mm in length were cast with different percentages of regular and irregular shape recycled plastic waste fibers of 0, 15, and 30% volume fractions. The test results indicated a minor drop in the yield load and ultimate load capacities and secant stiffness of the beams, while developments in the initial stiffness and ductility were recorded. Mohammed and Aayeel (Mohammed & Aayeel, 2020) conducted flexural tests on sixteen reinforced concrete beams incorporating recycled expandable polystyrene (EPS) as a partial replacement of the mixture coarse aggregate. The partial replacements were 0, 15, 20, 25, 35, 45, and 60% by the volume of the natural coarse aggregate. The results revealed a continuous decrease in peak and ultimate loads as the EPS percentage replacement increased, where a drop in the beam’s load carrying capacity of 13.8 to 26.3% was recorded, while the cracking load was higher than the reference beam for all replacement ratios. The results also showed that all beams with EPS exhibited lower flexural ductility by more than 20% compared to the reference beam. However, the authors concluded that beams with up to 35% replacements showed acceptable flexural behavior while increasing the percentage of replacement led to lower performance. Adnan and Dawood (Adnan & Dawood, 2021) investigated the effect of mixtures’ sand partial replacement by fine particles made of plastic-box waste on the flexural behavior of reinforced concrete beams. Normal concrete mixtures with plastic-box waste replacement ratios of 0, 5.0, and 10.0% were adopted. Three beams with 1400 mm length were tested in four-point bending till failure. The results revealed that the beam with 5% plastic waste replacement exhibited a slight increase in cracking and ultimate load capacity, ductility, and stiffness, while the failure mode of all beams was similar to that without any plastic waste replacement. On the other hand, the beam with 10% replacement showed a decrease in the yield and ultimate load capacities, while exhibiting the highest ductility among the tested beams.

The above review literature reveals the favorable environmental impact of utilizing plastic wastes in the concrete construction industry, which would contribute to minimizing the earth and ocean environment pollution and decrease carbon dioxide emissions. It is shown in the reviewed literature that extensive research works were conducted to evaluate the influence of using different types of plastic wastes on concrete strength and durability. The vast majority of these researchers investigated the potential of using the plastic PET wastes as fibers and by a lesser percentage as a fine aggregate replacement, while fewer articles tried to examine the replacement of natural coarse aggregate by plastic wastes. On the other hand, most of the available literature investigated the materials-scale tests, while much lesser articles were found on the flexural behavior of reinforced concrete beams. From these articles, only a very limited number tried to study the incorporation of plastic waste particles as a partial replacement of the natural coarse aggregate in normal strength concrete. To the best of the authors’ knowledge, no previous study has investigated the influence of recycling plastic-boxes waste which is categorized from its properties the high-density polyethylene (HDPE) as a coarse aggregate replacement on the flexural behavior of high-strength reinforced concrete beams. To fill this gap, this research presents a pioneering experimental structural application in sustainable concrete to evaluate the flexural behavior of high-strength reinforced concrete beams by using plastic-box wastes (HDPE) as coarse aggregate particles and silica fume as a partial replacement of cement.

3. The experimental work
As preceded, this study aims to evaluate the efficiency of using plastic wastes as coarse aggregate partial substitutions in structural concrete. Hence, this efficiency was measured on the structural
scale where reinforced concrete beams 180 × 280 mm in cross-section, and 2000 mm in length containing plastic waste aggregate were tested in bending. Thus, the influence of plastic waste on the structural behavior of the reinforced concrete beams was assessed.

3.1. Materials and mixtures
This study used ordinary Portland cement type I from local manufacturers for all mixtures. The cement was manufactured following the recommendations of Iraqi Standard No. 5/1984 (Iraqi Standard Specification No. 5, 1984) and has the chemical composition and physical properties listed in Table 1. Silica fume was also used in the mixtures of this study as a secondary binder, which was adopted as a partial replacement of cement. Silica fume is known for its significantly finer particles compared to cement and thus is used to improve the strength and durability characteristics of the mixtures. The silica fume used was Mega Add MS (D), which has the chemical composition and physical properties listed in Table 2. Local natural sand from Al-Kut city was used as the fine aggregate, while local natural gravel was adopted as the mixtures' coarse aggregate. The maximum particle sizes of the fine and coarse aggregates were 4.75 and 10 mm respectively. The sieve analysis and properties of the sand and gravel were tested per the Iraqi Standards No. 45/1980 (Iraqi Standard Specification No. 45, 1984). The physical properties of the used sand and gravel are listed in Table 3, while their grading analyses are shown in Figure 1. Both aggregates were well washed and surface dried before being used to remove the dust and other pollutants from the particle surfaces.

The recycled plastic coarse aggregate was made in this study using the vegetable plastic boxes shown in Figure 2a. The boxes were first collected and shredded into small pieces that are similar in size to the coarse aggregate utilized in the concrete industry. The shredding machine shown in Figure 2b was utilized to cut the plastic boxes. After collecting the required quantity (Figure 2c), the

| Table 1. Chemical composition and physical properties of cement |
|---------------------|-----------------|-----------------|-----------------|
| Oxide     | Content (%) | Property | Value |
| CaO       | 61.61       | Loss of Ignition (%) | 1.38 |
| SiO₂      | 20.08       | Specific Surface (m²/kg) | 368 |
| Al₂O₃     | 4.62        | Specific Gravity | 3.15 |
| Fe₂O₃     | 3.6         | Initial Setting Time (min) | 65 |
| S O₃      | 2.71        | Final Setting Time (min) | 170 |
| MgO       | 2.12        | Compressive Strength 7 Days (MPa) | 27.4 |
| C₃A       | 6.16        | Compressive Strength 28 Days (MPa) | 46.8 |

| Table 2. Chemical composition and physical properties of silica fume |
|---------------------|-----------------|-----------------|-----------------|
| Oxide     | Content (%) | Property | Value |
| SiO₂      | 91.4        | Bulk Density (kg/m³) | 500–700 |
| CaO       | 1.32        | Specific Surface | 15,000 |
| Al₂O₃     | 0.79        | Specific Gravity | 2.1–2.4 |
| Fe₂O₃     | 5.29        | Pozzolanic Activity Index (7 days) | 105% |
| S O₃      | 0.53        | Particles Retained on the 45 μm Sieve | < 10% |
| MgO       | 0.43        |                |               |
| K₂O       | 1.03        |                |               |
| Na₂O      | 0.23        |                |               |
recycled plastic pieces were washed and air dried and then sieved using the standard coarse aggregate sieves as depicted in Figure 2d. Then after, the recycled plastic pieces were grouped and bagged according to their particle size based on the previous sieve analysis as shown in Figure 2e. The color and shape of the plastic pieces were different according to the source box color and box.
part, yet, the pieces were mostly flat shaped. To utilize the recycled plastic pieces as a coarse aggregate, the different particle sizes were mixed according to the required percentages to form a graded coarse aggregate, where the plastic pieces were mixed to have the same sieve analysis of the natural gravel shown in Figure 1, while the physical properties of the recycled plastic waste aggregate are listed in Table 4. To achieve the required workability, Visco Crete-5930 superplastitizer (SP) from Sika was used for all mixtures, which is provided by the manufacturer as a turbid liquid with a specific gravity of approximately 1.08.

Different diameters grade 60 deformed reinforcing steel bars were utilized in the reinforced concrete beams of this study. The tensile bars of the beams were 16 mm in diameter, while 12 mm bars were used as top holding bars. On the other hand, 10 mm diameter bars were utilized as stirrups to fulfill the shear requirements and to prevent unfavorable diagonal tension failure. Samples from the three bars were tested in the Construction Materials Laboratory at the College of Engineering/ Wasit University per the recommendations of ASTM A615-16 (ASTM A615/A615M-16, 2016). The test results of the physical properties of the three bars are summarized in Table 5.

Several trial mixtures were cast and tested to reach a high strength and good workability concrete mixture that can be used for structural applications. After choosing the most successful mixture, another set of trial mixtures was cast and tested to evaluate the effect of the recycled plastic waste on the strength and workability of the mixture. In addition to the reference mixture that includes no plastic wastes, three mixtures with three weight percentage substitutions of 10, 20, and 30% of recycled plastic wastes by the natural gravel were tested. The details of the four mixtures are listed in Table 6. It should be mentioned that B0 refers to the reference mixture without recycled plastic wastes, while B10, B20, and B30 refer to the mixtures with plastic waste replacements of 10, 20, and 30%, respectively.

### 3.2. The reinforced concrete beams

The reinforced concrete beams presented in this study were designed per the recommendations of ACI 318–14 (ACI 318-14, 2014) to fail in flexure. The beam cross-section was 180 mm in width and 280 mm in depth, while the total length of the beam was 2000 mm. All beams were reinforced with 2016 mm bottom tension and 2010 mm top bars. On the other hand, Ø10 mm closed stirrups were distributed along the shear spans at a center-to-center spacing of 100 mm to prevent shear

### Table 4. Physical properties of the recycled plastic coarse aggregate

| Property                  | Value | ASTM Standard                                |
|---------------------------|-------|----------------------------------------------|
| Density (kg/m³)           | 0.949 | ASTM D792 (ASTM D792-20, 2020)              |
| Water Absorption          | 0     | ASTM D570 (ASTM D570-98R18, 2018)           |
| Modulus of Elasticity (MPa)| 358.7 | ASTM D638 (ASTM D638-14, 2014)              |
| Compressive Strength (MPa)| 26.4  | ASTM D695 (ASTM D695-15, 2015)              |
| Tensile Strength (MPa)    | 7.7   | ASTM D638 (ASTM D638-14, 2014)              |
| Flexural Strength (MPa)   | 878.3 | ASTM D790 (ASTM D790-17, 2017)              |

### Table 5. Properties of reinforcing steel bars

| Nominal Diameter (mm) | 10  | 12  | 16  |
|-----------------------|-----|-----|-----|
| Actual Diameter (mm)  | 9.85| 11.73|15.93|
| Yield Stress (MPa)    | 565.56| 640.01| 526.49|
| Ultimate Strength (MPa)| 645.5| 713.83| 631.22|
| Total Elongation (%)   | 10  | 9.28| 13.67|
failure. The concrete bottom cover was 30 mm, which afforded an effective depth of 232 mm, and hence the steel ratio was approximately 0.96%. Four identical beams were cast from the four concrete mixtures detailed in Table 6. Thus, the beams have the same identification number as the mixtures, where the main goal of the tests is to evaluate the effect of using recycled plastic wastes on the flexural performance of reinforced concrete beams. Figure 3 illustrates the geometrical details and reinforcement of the concrete beams. The reinforced concrete beams were cast using plywood forms and were cured in water for 28 days at an approximate temperature of 25 °C. Figure 4 shows the preparation of the beam forms and the molds of the standard concrete test that were cast and tested with each beam. Where with each beam (from each of the four mixtures), three: 150 mm cubes were cast to evaluate the weight and compressive strength, 100 mm diameter and 200 mm depth cylinders were used to test the splitting tensile strength, and 100 × 100 × 400 mm prisms were used to evaluate the modulus of rupture.

### 3.3. The test setup

The beams were tested over a simple span using the four-point bending test as shown in Figure 5. The test span was 1800 mm, while the distance between the two-point loads was 600 mm, which means that the length of each of the shear spans was 600 mm. The load was applied monotonically and gradually from the hydraulic testing machine, while the cracking was observed at each load step. The load was recorded using a 1000 kN load cell, while the deflection was recorded at the center of the span using a Linear Variable Differential Transformer (LVDT) as shown in Figure 3.

| Mixture | B0  | B10 | B20 | B30 |
|---------|-----|-----|-----|-----|
| Cement | 446.25 |
| Silica Fume | 78.75 |
| Sand | 625.75 |
| Gravel | 945 | 850.5 | 756 | 656.5 |
| Plastic waste | 0 | 94.5 | 189 | 288.5 |
| W/B* | 0.27 |
| Water | 131.25 |
| SP | 7.88 |

* B = Binder = Cement + Silica fume

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**Table 6. Mix proportions (kg/m³)**

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**Figure 3. Geometry and reinforcement details of the reinforced concrete beams.**
4. Results and discussion of the control tests

The results which have been evaluated for the weight of the mixture are 8.45 Kg, 7.96 Kg, 7.57 Kg, and 7.46 Kg for B0, B10, B20, and B30 according to the order, with a decrease of 5.76%, 10.4%, and 11.83% for B10, B20, and B30 respectively from B0. The test results of the compressive strength \((fc)\) are depicted in Figure 6 for the four mixtures. It is clear in the figure that the compressive strength exhibited a continuous reduction with the increase of the substitution percentage of the recycled plastic wastes. The compressive strength values of the specimens with 10, 20, and 30% of recycled plastic waste were 54.6, 51.5, and 42.7 MPa, respectively, while the recorded strength of the reference mixture without plastic waste was 63.4%. This means the compressive strength was reduced by approximately 14, 19, and 33% as 10, 20, and 30%, respectively of the natural gravel was substituted by recycled plastic waste. The obtained results of the high-strength concrete mixtures are in full agreement with literature results (Jacob-Vaillancourt & Sorelli, 2018; Jain et al., 2019; Mercante et al., 2018; Mohammadinia et al., 2019; Mohammed et al., 2019) that
revealed a similar trend of results for normal-strength concrete mixtures made with different types of plastic waste aggregates.

On the contrary, Figures 7 and 8 show that the splitting tensile strength and modulus of rupture exhibited a strength increase as the percentage replacement of natural coarse aggregate by shredded plastic box particles increased. The increase in the splitting strength was proportional to the replacement ratio, where the splitting strength of the reference mixture (B0) was 6.3 MPa, while the mixtures B10, B20, and B30 recorded splitting strength values of 6.57, 6.88, and 7.0 MPa, respectively. Hence, the percentage replacements of 10, 20, and 30% led to an increase in the splitting strength of approximately 4, 9, and 11%, respectively compared to the reference specimens. Similarly, the modulus of rupture records of the mixtures B0, B10, B20, and B30 were 4.4, 5.97, 6.03, and 6.54 MPa, respectively. Thus, the flexural strength was improved by approximately 36, 37, and 49% as 10, 20, and 30% of the recycled plastic waste aggregate particles were incorporated. A possible explanation for the drop of the compressive strength and the increase of the splitting tensile strength and modulus of rupture is the type of stresses induced under each test. Compressive stresses are induced in the concrete cubes under the concentric compression loading, which means that the crushing strengths of the aggregate and cement matrix are the main control factors. Since the crushing strength of the natural gravel is much higher than plastic particles, the strength exhibited a continuous decrease with the increase of these particles. On the other hand, the controlling stresses under splitting and flexural tests are tensile. Thus, the incorporation of the HDPE plastic coarse aggregate particles with an irregular shape that attains an adequate anchorage in the cement matrix help to absorb a part of the tensile stresses across the internal cracks owing to its better ductility, which in turn slowed down the widening of the tensile cracks and hence postponed the failure of the specimen.
5. Results and discussion of reinforced concrete beams

As preceded, this study aims to evaluate the efficiency of using plastic wastes as a coarse aggregate partial substitution in concrete structurally. Hence, this efficiency was measured on the structural scale where reinforced concrete beams containing plastic waste aggregate were tested in bending. Thus, the influence of plastic waste on the structural behavior of the reinforced concrete beams could be assessed.

5.1. Cracking and failure patterns

Figure 9 includes the pictures that show the final cracking patterns of the four reinforced concrete beams at failure, while the cracking (Pcr), yield (Py), peak (Pp), and failure (Pf) loads, in addition to the failure pattern, are listed in Table 7 obtained from strain gages' data and load-deflection curve findings. It is obvious in the figure that all beams regardless of the percentage substitution of plastic waste by coarse aggregate exhibited the typical ductile cracking and failure patterns of under-reinforced concrete beams. As the load approaches the service limit, the stress at the extreme bottom tension fiber exceeds the tensile strength of concrete (modulus of rupture), which initiates the flexural cracking at this fiber. With the increase of the load beyond this limit, firstly initiated cracks get wider and new cracks develop. This scenario was observed for all beams tested in this study, where pure flexural cracks appeared in the flexural zone between the two-point loads after the initiation of the first crack. The first crack appeared at a load of approximately 24 to 27% of the maximum load capacity of the beams, which is termed peak load (Pp) in this study. As the load was monotonically increased beyond the cracking load, more flexural cracks were initiated from the tension surface among the flexural zone, while the firstly initiated cracks propagated vertically towards the neutral axis. This trend continued and the propagation of cracks continued upward as the load was further increased, which was followed by the initiation of flexural cracks out of the pure flexural zone (along the shear spans). These cracks were then turned inward forming what is known as flexural-shear cracks that started vertical and then inclined towards the point loads. The increase of the applied load to approximately 73% to 85% of the peak load resulted in the yield of the tension reinforcement, which was associated with the noticeable widening of one or more flexural cracks. The increase of the applied load beyond the yielding limit led to a significant widening and propagation of several cracks, which was finalized by the failure of the beam by the fracture of the concrete compression zone at one of the loading points as shown in Figure 9. This failure occurred due to the yielding of the tension reinforcement which was followed by reaching the ultimate compression strain of concrete, which is the preferable structural failure of reinforced concrete flexural members. The multi-cracking of the beams reflects the ductile behavior and failure of the four beams regardless of the quantity of the plastic waste aggregate used, which is clear by the comparison of the cracking patterns of the four beams B0, B10, B20, and B30.
5.2. Load-deflection behavior

The load-deflection curves of the four beams are illustrated in Figure 10, which shows the behavior till the point of load drop after failure. It is clear in the figure that the four beams exhibited the required ductile performance of under-reinforced beams, which assures the results discussed in the previous section. All beams exhibited a linear or semi-linear increase of deflection with the increase of load up to the first cracking point, where a local drop followed by a close subsequent rise in load was observed as shown in Figure 10. The first cracking was observed at a load of approximately 116 kN for the reference beam B0. On the other hand, the cracking load of the three beams with recycled plastic waste was between approximately 97 and 109 kN. After the first crack became visible, new cracks were developed and got wider as the load was increased, which is clear in the local load drop-rise fluctuations in the load-deflection curves after the points of the first crack appearance. Although of these local load fluctuations, the general trend of the average load kept approximately linear with the corresponding deflection along this zone. However, the slope of this line changed showing lower stiffness compared to the initial stiffness up to the first cracking. As shown in the load-deflection curves drawn in Figure 10, the point of the first cracking represented a slope-changing point. Although, the two lines can be considered as one zone of an

![Figure 9. Cracking patterns at the failure of the reinforced concrete beams.](image)

| Beam | Pcr* kN | Δcr*8 mm | Py* kN | Δy** mm | Pp* kN | Δp** mm | Pf* kN | Δf** mm | Failure Mode |
|------|---------|----------|--------|---------|--------|---------|--------|---------|--------------|
| B0   | 115.87  | 0.8133   | 322.75 | 7.174464| 435.6  | 37.7    | 380    | 42      | Flexure      |
| B10  | 108.94  | 1.502    | 330.59 | 8.590432| 403.7  | 26.85   | 280.225| 43.43   | Flexure      |
| B20  | 99.39   | 1.949    | 290.29 | 9.29454 | 396.96 | 30.35   | 328.12 | 44.39   | Flexure      |
| B30  | 96.59   | 1.38     | 344.04 | 9.042968| 405.78 | 46.41   | 350.59 | 52.03   | Flexure      |

*crack, yield, peak, and failure loads

** crack, yield, peak, and failure deflection

Table 7. Loads, deflections, and failure modes of the tested beams

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approximately linear response. As disclosed in the previous section, after exceeding approximately three-fourths of the beams’ load capacity, the tensile steel yielded, where the steel yield of the four beams occurred between approximately 290 and 344 kN. Starting from this point, the slope of the load-deflection curve changed noticeably towards a flatter line where a second zone can be distinguished in its behavior. This zone can be identified by a significant decrease in the stiffness after the first zone kept approximately a semi-constant slope. The yield of steel initiated the quick deformation zone which is identified by a plastic plateau that extended hardening up to the maximum load capacity, which is termed as the peak load (Pp) in this research. Up to this point, the behavior of the four beams is approximately similar with different load values. What distinguishes the four beams from each other is the post-peak zone, where the reference beam exhibited a continuous hardening till the peak load followed by a steep drop very close to failure as shown in the figure. On the other hand, the beams containing 10% and 20% of recycled plastic waste coarse aggregate exhibited a significant softening and slow drop in load till failure. Where the reference beam showed only 4.3 mm extra deflection after the peak load till failure, while the beams B10 and B20 showed 16.6 and 14 mm additional deflection from peak to failure. This behavior can be attributed to the bond between the recycled plastic aggregate particles and the surrounding cement matrix that allowed for extra crack widening and hence more deflection with load decrease. However, increasing the plastic waste percentage to 30% improved the plastic behavior of beam B30 which exhibited a longer plastic plateau and harder deflection behavior after peak load compare the beams B10 and B20. This percentage might represent an optimum substitution quantity so that the anchorage of the recycled aggregate particles with the surrounding cement matrix became better. Higher bond strength means higher tensile stresses can be carried by the plastic waste particles which improved the overall plastic behavior of the beam.

5.3. Effect of recycled plastic waste on the load capacity of the reinforced concrete beams
The direct influence of the incorporation of plastic waste particles as a partial replacement of the natural coarse aggregate on the cracking load capacity (Pcr) is depicted in Figure 11, while Figures 12 and 13 show this effect on the retained yield (Py) and peak (Pp) loads, respectively. It is obvious in Figure 11 that the increase of the plastic waste percentage replacement from zero to 10, 20, and 30% led to a proportional decrease in the cracking load of the reinforced concrete beams. As listed in Table 7, the cracking load of the reference beam B0 without recycled plastic waste aggregate was approximately 116 kN, while the incorporation of 10, 20, and 30% of recycled plastic waste aggregate reduced the cracking load by approximately 6, 14, and 17%, respectively. From previous studies (Adnan & Dawood, 2020, 2021) which used plastic as a sand replacement in concrete, no relation between the test results of splitting strength ft and flexural strength fr and the test results recorded for initial cracks load of the beams with the increase in percentages of plastic.
On the other hand, it is clear in Figure 12 that increasing the percentage replacement of aggregate by plastic waste particles has no clear influence on the yield load of the tested beams. This result agrees with what was reported by previous researchers (Adnan & Dawood, 2021). Where except for beam B20, the yield load of beams with recycled plastic aggregates was higher than the reference beam by no more than 7%. It might be said that owing to the elastic behavior of the plastic particles, a part of the tensile stresses across the cracks was carried by these plastic particles which relieved the stress on the tension bars and resulted in postponing their yielding, while for the same reason, the cracks were opened more quickly resulting in lower cracking loads. Finally, Figure 13 shows that all beams with recycled plastic waste exhibited a lower peak load compared to the reference beam by approximately 7 to 9%. This result is in full agreement with previous studies where plastic wastes reduced the beam’s ultimate load capacity (Adnan & Dawood, 2020, 2021; Mohammed & Aayeel, 2020). From the standpoint of
crushing strength, hardness, and stiffness, natural aggregates are superior to recycled plastic waste aggregates. Therefore, it is expected that the peak load capacity would be reduced by such a kind of substitution. However, considering the positive environmental impact of this replacement, it can be said that a reduction in the strength of 7% is quite acceptable when compared with the advantages of the 30% replacement of the natural aggregate by the plastic waste particles, keeping in mind that aggregates compose the largest portion of the concrete volume.

5.4. Flexural ductility of the reinforced concrete beams

Flexural ductility is known as a measurement that expresses the plastic capacity of the beam in flexure, or its ability to absorb plastic deformation before failure. The term ductility index is the typical numeral expression of flexural ductility. It is simply obtained by dividing the ultimate deformation by that at the yield of steel reinforcement, where the yield can be considered as the limit at which the beam behaves plastically and the hardening plateau of deformations or strains starts. The previous researchers introduced several definitions to determine the ultimate deflection. Some previous studies used the deflection at which the load drops vertically as the ultimate deflection (Bernardo & Lopes, 2004; Yang et al., 2010). Others used the deflection corresponding to 80% of peak load at the post-peak region as the ultimate load (Abbass, Abid, Arnaot et al., 2019; Abbass et al., 2021; Chunxiang & Patnaikuni, 1999; Hadi & Elbasha, 2007; S.W. Shin et al., 1989), while others used the deflection corresponding to 85% (Al-Gasham et al., 2020; Dancygier & Berkover, 2016; Lopes et al., 2012; Nogueira & Rodrigues, 2017; Pam et al., 2001) and 99% (S-W. Shin et al., 2010) post-peak load. In this study, the most adopted terminology was adopted where the deflection corresponding to 85% of the peak load at the post-peak region was adopted as the ultimate deflection. On the other hand, the yield deflection was that corresponded to the experimentally recorded yield load that was recorded using the strain gauges attached to the tension reinforcement. It is clear in Figure 14 that the ductility has decreased for all beams with recycled plastic aggregate compared to the reference beam, where a percentage reduction of approximately 24% was recorded for beams B10 and B20, which agrees with the results obtained for peak load. Where for these two beams, both the peak and ultimate load capacities were decreased compared to the reference beam. Considering the post-peak softening behavior of these beams discussed in Section 4.2 and shown in Figure 10, and taking into account the definition of the ultimate deflection for ductility calculations, the ultimate deflections of beams B10 and B20 were lower than that of the reference beam B0. Keeping in mind the higher recorded deflections corresponding to the yield load of the two beams, a noticeable reduction in ductility was recorded. On the other hand, the reduction in the ductility of the beam with 30% of recycled plastic waste was too limited, which was less than 2%. Hence, it can again be concluded that adding 30% of recycled plastic waste as a substitution of the natural coarse aggregate does not noticeably affect the structural performance of the reinforced concrete beam. In some previous studies, it was reported that for structural requirements of high seismic zones, a ductility of not
less than 3 is required (Abbass, Abid, Özakça et al., 2019; S-W. Shin et al., 2010). As shown in Figure 14, the ductility of all beams with recycled plastic aggregate was more than 4.4, which again reinforces the conclusion of the applicability of using plastic waste as a partial replacement for natural coarse aggregate.

5.5. Flexural stiffness of the reinforced concrete beams

Flexural stiffness is the ratio of the load to the corresponding deflection. To measure the initial stiffness, two practical values can be used. In the first, the cracking stiffness can be introduced as the initial stiffness, where it represents the slope of the linear line connecting the origin of the load-deflection curve and the point of the first cracking. This line is approximately linear and can be introduced to represent the initial stiffness because it includes the recorded load-deflection points and the beam’s capacity service range. On the other hand, as discussed in the previous sections, the slope of the region from cracking to yielding changes slightly from the initial line’s slope up to cracking. However, the trend in this region is still approximately linear. Therefore, the second definition of the initial stiffness considered in this work is yield stiffness, which represents the slope of the line extending from the origin point of the load-deflection curve to the yield point. This stiffness is termed yield stiffness and is simply calculated by dividing the yielding load by the corresponding deflection at this load.

Figure 15a shows that the stiffness till the cracking point suffered noticeable degradation for beams with recycled plastic waste compared to that of the reference beam. Where the recorded cracking stiffness of the reference beam B0 was approximately 142 kN/mm, while the corresponding cracking stiffness values of the beams B10, B20, and B30 were approximately 73, 51, and 70 kN/mm. This means that the cracking stiffness was reduced by approximately 49, 64, and 51%, respectively as 10, 20, and 30% of the natural coarse aggregate was replaced by recycled plastic waste particles. A similar but lighter trend of decrease was also recorded for the yield stiffness (Figure 15b) which was reduced from approximately 45 kN/mm for B0 to 39, 31, and 38 kN/mm for B10, B20, and B30, respectively. Hence stiffness reductions of approximately 14, 31, and 15% were recorded as the natural coarse aggregates were partially replaced by 10, 20, and 30% of recycled plastic waste.

5.6. Flexural toughness of the reinforced concrete beams

Flexural toughness is a measurement of the dissipated energy that the beam can absorb under flexural loading. This flexural toughness is simply obtained by integrating the area under the load-deflection curve, which composes of different parts as depicted in Figure 16, where this area can be divided based on the effective transition points that control the response of the concrete beam under the bending test. The effective points in the flexural behavior are the cracking point, yield point, peak point, and ultimate point. The area under the curve from the origin up to the cracking point can thus be defined as the cracking toughness (Tcr), while the area from cracking to yield can be defined as yield toughness (Ty). Similarly, the area following the yield point till the maximum retained load (peak load) can be defined as the peak toughness (Tp), while from peak till failure (ultimate load) composes the ultimate toughness (Tu) as described in Figure 16. Thus, the toughness of the beam or the total toughness, which is the total area under the load-deflection curve, is simply the sum of Tcr, Ty, Tp, and Tu. Table 8 lists the obtained values for the cracking, yield, peak, and ultimate toughness in addition to their summation or the total toughness, while Figure 17 shows the obtained values of Tcr, Ty, Tp, and Tu for the four beams B0, B10, B20, and B30. It is shown in Table 8 and Figure 17 that the cracking toughness of the beams incorporating recycled plastic waste aggregates was higher than that of the reference beam by 32 to 95%. This result was obtained due to the higher initial cracking stiffness of the reference beam. The degradation of stiffness means exhibiting higher deflections at the same loads, which of course increased the toughness. Similarly, the yield toughness of beams B10, B20, and B30 was higher than that of the reference beam B0 by 14 to 32%, which is also attributed to the degradation of the initial yield stiffness of these beams compared to beam B0. On the other hand, the yield load and the
lower peak load of beams B10 and B20 resulted in lower peak toughness of these beams compared to the reference beam by 30 to 34%, while the moderately high peak load of B30 and its highest peak deflection retained the peak toughness of this beam to slightly higher than that of the beam B0. As shown in Figure 10, the post-peak regions of the load-deflection curves of beams B10, B20, and B30 were noticeably longer than that of beam B0. Therefore, their ultimate toughness values were significantly higher than that of the beam B0 as listed in Table 8 and shown in Figure 17. In Figure 18 we can see that the total stiffness of the beams B10 and B20 was reduced slightly by approximately 3 to 4%, while the total toughness of the
beam B30 increased by 24% compared to the reference beam B0, which is a very encouraging result that indicates the adequacy of utilizing recycled particles from plastic-boxes as a 30% replacement of the natural coarse aggregate.

6. Conclusions
Based on the recorded test results from the flexural tests conducted in this study, the following conclusions can be drawn:

1. The beams with recycled plastic waste coarse aggregate exhibited the same ductile multi-cracking pattern and flexural failure of the reference beam regardless of the substitution percentage of plastic waste by the natural aggregate, which reflects the preferable flexural behavior of these beams and hence their suitability for structural applications.

Table 8. Flexural toughness of the reinforced concrete beams

| Beam | Tcr kN.m   | Ty kN.m   | Tp kN.m   | Tu kN.m   | Total Toughness kN.m |
|------|------------|-----------|-----------|-----------|----------------------|
| B0   | 61.04787   | 1410.302  | 11,694.51 | 1945.565  | 15,111.43            |
| B10  | 100.7599   | 1680.458  | 6930.507  | 5917.916  | 14,629.64            |
| B20  | 119.2361   | 1552.657  | 7581.312  | 5225.492  | 14,478.7             |
| B30  | 80.7712    | 1860.688  | 12,593.08 | 4209.697  | 18,744.24            |

Figure 17. Cracking, yield, peak, and ultimate flexural toughness of the reinforced concrete beams.

Figure 18. Total toughness of the reinforced concrete beams.
The flexural test results showed that the cracking load was decreased by 6, 14 and 17% as the natural coarse aggregate was partially replaced by 10, 20, and 30% of shredded particles of the plastic boxes, while such a clear trend of the result was not recorded for the yield load, that the yield load was mostly slightly higher than that of the reference beam. This behavior is due to the contribution of the plastic particles in carrying tensile stresses, which accelerated the cracking and relieved the tensile stresses in the steel bars leading to higher yield loads.

The beams with partial substitution of natural coarse aggregate by plastic waste particles retained lower load capacity (peak load) compared to the reference beam by 7 to 9%, that the weaker physical properties of the recycled plastic aggregates compared to the natural gravel. The ductility of the beam with 30% substitutes was also minimally reduced by less than 2% compared to the reference beam. Thus, considering the positive environmental impact of this replacement, it can be concluded that the 7% reduction in strength and the 2% reduction in ductility are quite acceptable when compared with the environmental advantages of the 30% replacement of the natural aggregate plastic waste particles.

The initial stiffness of the beams exhibited a significant reduction for beams with recycled plastic waste compared to the reference beam. Where the slope of the load-deflection curves up to the cracking point (cracking stiffness) was reduced by 49, 64, and 51% as the natural coarse aggregate was partially replaced by 10, 20, and 30%, respectively, of recycled plastic waste particles. Similarly, the slope of the line from the origin point of the load-deflection curve to the yield point (yield stiffness) for beams with 10, 20, and 30% of recycled plastic waste coarse aggregate was decreased by 14, 31 and 15%, respectively, compared to the reference beam with 100% natural coarse aggregates.

The cracking and yield toughness of the beams with recycled plastic waste aggregate were higher than those of the reference beam owing to their lower initial stiffness values, while their ultimate toughness values were higher due to their post-peak better plastic response. The total toughness of the beams with 10 and 20% replacements of plastic waste aggregate by natural coarse aggregate was approximately equal to that of the reference beam while incorporating a 30% replacement increased the total toughness by 24%.

In a nutshell, the partial substitution of 30% of the high-strength concrete mixture’s coarse aggregate by shredded plastic box particles is recommended for its favorable environmental impact and acceptable structural performance. Where the load carrying capacity and ductility were approximately similar to the reference beam, while the total toughness was higher by more than 20%.

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