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Structural Performance of Ferrocement Beams containing Plastic Waste Fibers and Longitudinal Holes Filled with Lightweight Concrete

AR. Jamal Alobeadi[a*] , Abdulkader Ismail Al-Hadithi[a] , Muhannad H. Aldosary[a]

[a]*Civil Engineering Department, College of Engineering, University of Anbar, Anbar, Iraq*

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ABSTRACT

Ferrocement is a type of concrete made from mortar combined with different wire meshes. It has a wide range of applications due to its strength and durability. This research aims to integrate ferrocement with sustainability, as the consumption of plastics, particularly plastic bottles, has increased over time, leading to serious negative effects when these materials are buried, burned, or chemically processed. Therefore, this study seeks to utilize plastic waste by incorporating plastic waste fibers into the concrete mixture, replacing a portion of the concrete mix volume at rates of 0.5% and 1% by volume.

The research examined the mechanical properties of nine samples of ferrocement beams with dimensions of 1200 × 200 × 150 mm^3. A longitudinal hole with a diameter of 50 mm was drilled at various locations in the beams and filled with lightweight concrete to allow for service passes when drilled. The study included an analysis of the initial cracking loads, the resulting deflection, and the failure modes associated with the maximum load.

The results showed an improvement in load resistance along with enhanced deflection performance at maximum load, as well as increases in the toughness and stiffness of the ferrocement beams.

1. Introduction

Ferrocement is a reinforced concrete constructed from hydraulic cement mortar and has a thin wall reinforced using various wire meshes, either metal or otherwise. This is the definition of ferrocement as published by (A. C. I. Committee 549 2018) Committee. Ferrocement concrete differs from traditional reinforced concrete in that it is reinforced with wire meshes with a smaller diameter than the known reinforcing steel and in several layers. Ferrocement is characterized by strength, hardness, and flexibility. It can be formed into different shapes for easy folding. The thickness of ferrocement ranges from 25 mm to 50 mm (A. C. I. Committee 549 2018). Ferrocement

* *Corresponding author*. Tel.: +9647812355219
E-mail address: abd22e1003@uoanbar.edu.iq

is considered an old form of reinforced concrete, as it has not been highlighted until recent years. Despite the similarity between it and concrete, there is a big difference in properties as Lalaj's group mentioned that concrete is characterized by compressive strength. Still, ferrocement has very good compressive strength, bending, and tensile behavior, while it does not have high durability in reinforced concrete. This is due to the thin ferrocement cover and sections ,and it is very suitable for strengthening ceilings, beams, columns, and walls, in addition to the ability to give the desired architectural shape. This is due to its softness and ease of shaping before drying. In all cases, ferrocement can improve structural elements' properties, provided there is good bonding between ferrocement and the structural element (Lalaj, Yardım, & Yılmaz, 2015). According to research by Shaheen's team, lightweight concrete reinforced with plastic fibers can achieve structural efficiency. Ferrocement is an intriguing and adaptable substance with little attention and a wide range of potential uses (Shaheen, Eltaly, Yousef, & Fayed, 2023). As Ismail and AL-Hashmi (2008) mentioned, it is less expensive than conventional reinforced concrete structures. In addition, due to its torsional stiffness and ability to withstand flexural and small shear stresses, it is also a good pattern for flexural stresses.

Polyethylene terephthalic (PET) is a semi-crystalline polymer with a high molecular weight. It consists of ethylene glycol and terephthalic acid, as explained by Webb's team (Webb, Arnott, Crawford, & Ivanova, 2012), (PET) has a chemical formula of ($C_{10}H_8O_4$). It is considered one of the world's most widespread types of polyester in terms of packaging industries and plastic bottles for soft drinks. Dhaka's team confirmed that the process of burning plastic waste made of polyethylene terephthalate leads to the release of toxic gases into the atmosphere, including sulfur dioxide, chlorofluorocarbons, and nitric oxide, and also affects crops and makes their soil less fertile (Dhaka, Singh, Anil, Sunil, Kumar, Naik, Garg, Samuel, Kumar, Ramamurthy, & Singh, 2022). Li, Wang, Su, Zou, Duan, and Zhang (2021) confirmed that there are many ways to get rid of plastic, one of which is burning, where plastic is burned in factories, and this burning results in toxic pollution in the environment, as the workers responsible for this work suffer from cancer resulting from the fine plastic flying in the air. Alabi, Ologbonjaye, Awosolu, and Alalade (2019) recommend that a clean environment free from toxins resulting from plastic waste can be achieved through awareness and the enactment of laws that monitor the production, use, and disposal of plastic and prevent the use of toxic chemicals in its production.

The results of the study obtained by Askar, Selman, and Mohammed (2020), the use of plastic fibers in concrete enhanced the bonding, increasing the tensile strength by 13% when using 0.5% PET fibers, while the tensile strength increased by 19% when using 0.75% fibers. Rohden, Camilo, Amaral, Garcez, and Garcez (2020) confirmed that using plastic fibers in concrete decreased the percentage of voids, as the results showed an increase in acoustic impedance when the fiber content increased. Shen, Liu, Zeng, Zhao, and Jiang (2020) confirmed that using long plastic fibers decreased the absolute value of shrinkage, cracking resistance, cracking stress, and specific tensile creep. Another study showed that the compressive strength increased by 22.25% when using plastic bottle waste fibers compared to polypropylene and polyester. The bending test also improved, as the bending strength increased from 0.94 MPa to 5 Mpa (Khan, Umair, Shaker, Basit, Nawab, & Kashif, 2020). Askar, Al-Kamaki, and Hassan (2023) demonstrated the effect of Polyethylene Terephthalate (PET) on concrete. They used scanning electron microscopy (SEM) for a concrete sample containing PET it was found that the concrete sample had an irregular shape, which led to the formation of pores of approximately 4 micrometers. Cement formations surrounded by PET can be observed, improving the bonding property. They also reported that concrete containing PET reduced the percentage of microcracks. Abousnina and his group summarized in a study conducted using plastic fibers that enhanced the splitting-tensile strength by 28.7% and 41.9%, respectively. This is due to the uniform distribution of fibers that resist internal stresses and resist crack propagation (Abousnina, Premasiri, Anise, Lokuge, Vimonsatit, Ferdous, & Alajarmeh, 2021).

According to BS EN: 12390-3 and ASTM C293-15 specifications (ASTM C293/C293M, 2015; BS EN 12390-3, 2009), Ali's team studied the effect of plastic waste fibers in different proportions on ferrocement samples for compressive strength and flexural strength testing, where the test results gave a noticeable improvement in compressive strength. This is because the fibers in the test samples increased the adhesion strength and reduced voids. They were homogenized with the mortar mixture, making them more rigid and cohesive. In contrast, the flexural test results slightly improved when fibers were added to the samples in different proportions (Ali, Al-Hadithi, & Al-Asafi, 2024).

Fouad Al-Ami et al. [18] made concrete beams containing circular openings occupying 40% of the effective depth to study the effect of openings on the maximum load, first cracking load, and deflection. The results showed that beams containing openings less than 40% of the effective depth had no significant effect on the first and maximum cracking load. In comparison, openings occupying an area greater than 40% of the effective depth impacted the early appearance of cracks with a decrease in load resistance. They also showed that openings in the compression zone are closer to receiving the load because they are exposed to plastic deformation and brittleness. Al-Samadi group studied the effect of the shapes and dimensions of openings in concrete beams, where they made beams containing circular openings with diameters of 50 mm and 75 mm, a rectangular opening with dimensions of (100×50) mm^2, and a square opening with dimensions of (50×50) mm^2, all in two locations, one at a distance of 90 mm from the top of the section and the other at a distance of 160 mm from the top of the section. The test results showed that the failure mode was a flexural failure for the reference concrete beams containing openings. As for the pull, the beams with rectangular and square openings were less pulled than those with circular openings for the same location. As for the first cracking load for the beams with rectangular and square openings, it was greater than the load of the beams with circular openings, while the cracking load for the reference beams was greater than the cracking load for the beams with circular openings. As for the maximum load, the beams with circular and rectangular openings were less than the reference beams by 11% to 20%, respectively, while the beams with square openings were also less than the reference beams by 1 % (Al-Smadi, Al-Huthaifi, & Alkhawaldeh, 2022). Kumar, Garg, and Bahuguna (2021) studied the behavior of ferrocement beams reinforced with multilayer welded wire mesh and compared them with a reference beam. The test results showed that the ferrocement beams with openings had a weight saving of 20% to 30%. They also showed that the ferrocement beams reinforced with wire mesh showed an increase in first cracking load and maximum load and an increase in energy absorption.

Expanded polystyrene (EPS) is a lightweight material made from polystyrene granules that expand and coalesce during the heating process and is composed of approximately 98% air, as mentioned by Ramli Sulong, Mustapa, and Abdul Rashid (2019). It is very lightweight and has multiple uses and applications. Bedeković, Grčić, Anić Vučinić, and Premur (2019) showed that lightweight concrete containing expanded polystyrene (EPS) can be obtained in the laboratory and used as a filler. They confirmed that high compressive strength can be obtained when the cement and fine aggregate content increases. Abdel-Jaber's team explored expanded polystyrene (EPS) granules in rectangular concrete beams. The test results showed that concrete beams containing EPS had a lower compressive strength of 29.5% and a decrease in density of 11.1%. The EPS present in concrete beams reduced the ultimate bending capacity by 23.9% compared to the reference beam (Abdel-Jaber, Shatarat, & Katkhuda, 2023).

Previous literature on the construction of ferrocement beams reinforced with plastic waste fibers has indicated that some variables remain unexplored, including the use of plastic fibers in different proportions in ferrocement beams reinforced with welded wire mesh instead of stirrups, placing a longitudinal hole in the beams and filling them with mortar with Polystyrene (EPS). As a result, the work's subject is the structural performance of ferrocement beams with waste plastic fibers and longitudinal holes filled with lightweight concrete. A mixture was made for pouring ferrocement beams, replacing the cement with plastic fiber waste at rates of 0.5% and 1%, along with making a mortar mixture with EPS as lightweight concrete to fill the longitudinal holes in the circular-shaped beams in two different locations. This study determines the structural performance, such as cracking loads, ultimate loads, deflections, and failure, Toughness, and Stiffness.

2. Experimental Program

2.1. Ferrocement concrete (FC)

The components of ferrocement (FC) and the proportions used to produce it are listed in Table 1, which are ordinary Portland cement type (I), fine aggregate, and water. (FC) concrete was produced following (ACI 549.1R-93) (Batson et al., 1988). The chemical and physical properties of the fine aggregate were also consistent with Iraqi specifications (No. 45-1984) (IQS No.45, 1984). Compression (FC) samples were tested at 28 and were 39 MPa. The FC samples contained percentages of plastic fibers resulting from waste, as the plastic fibers are plastic containers that were manually cut into strips, as shown in Fig. 1, with dimensions of (70×5×0.4) mm^3, and the aspect ratio of the plastic fibers was 43.87. The tensile strength of the plastic fibers was 107 MPa, which was calculated in the laboratory using a very accurate device that measures thickness from 0 to 7 mm, and the load was applied to the sample until failure occurred. The first mixture was 0% plastic fiber-free. As for the second mixture, the cement was replaced with plastic fiber waste at a rate of 0.5%, and the compressive strength at 28 days reached 33 MPa. As for the third mixture, the replacement was 1%, and the compressive strength at 28 days reached 35 MPa, which was the average for all test samples.

2.2. Lightweight Concrete (LWC)

A mortar mixture containing polystyrene (EPS) was made, the mixing ratios mentioned in Table 1. The mixture comprises ordinary Portland cement, class I, fine aggregate, and sheet EPS granules. It was crushed manually to form small granules, as shown in Fig 2. As this mixture is considered lightweight concrete, water was used as a filler for the beam openings. It gave compressive strength at 28 days of 7.4 MPa on average for three samples.

Table 1 – Proportions and components of mixtures (Kg/m^3).

Mix	Cement	Fine aggregate	Water	EPS
FC	657	1314	296	0
LWC	238	716	119	9.5

Fig. 1 Plastic waste fibers (PET)

Fig.2 Polystyrene (EPS)

2.3. Reinforcement with Steel Bars

Reinforcing steel bars for FC. Steel with a diameter of 10 mm was used at the bottom in the tension zone and 6 mm at the top in the compression zone. The tests for the iron used were following the standards of the American Society for Testing and Materials (ASTM A615/A615M, 2015). The steel used has nominal yield and ultimate strength, as the f_y for each steel reached 6 mm and 10 mm were 396 MPa and 498 MPa, respectively, and the fu reached 499 MPa and 683 MPa, respectively.

2.4. Reinforcement with Steel Mesh

Welded wire mesh (WWM) with galvanized wires with square holes with dimensions of (25 × 25) mm^2 and a diameter of 1.1 mm was used, as shown in Fig. 3, to reinforce the shear areas in FC beams. Yield stress, Ultimate strength, and Modulus of elasticity were calculated for (WWM).457 MPa, 600 MPa, and 170 GPa, respectively.

2.5. Properties of Polyvinyl Chloride (PVC) Pipes

Polyvinyl chloride pipe (PVC) was used to make openings in the FC beams with an internal diameter of 50 mm, as shown in Fig. 4, as it is also considered completely resistant to water and electricity. The Tensile stress of (PVC) was calculated at 52 MPa. It was left inside the beams to determine the contribution of PVC to strengthening beams.

2.6. Beams Specimens

The experimental program of this research consists of nine beams divided into three groups; each group consists of three beams, each group consists of solid beams, and two beams containing a 50 mm diameter opening, one in the neutral axis region and the other below the neutral axis. The first group is denoted by (A). The first solid beam in the first group is considered a reference sample, denoted by (A1). The other groups containing 0.5% and 1% plastic fiber volume of fraction are denoted by (B, C), respectively. The beams' dimensions are (1200 × 200 × 150) mm^3, while the loading was 1000 mm long. Fig. 5 shows the shear reinforcement of the (FC) beams with two layers of (WWM). The stirrups were used as steel fixings, and the tension area at the bottom was reinforced with 10 mm diameter reinforcing steel. Fig. 6 shows a schematic diagram of the (FC) reinforcement beams.

Fig. 3 Welded wire mesh (WWM)

Fig. 4 Polyvinyl chloride pipe (PVC)

Fig. 5 Reinforcing steel for beams (FC)

3. Results and Discussion

3.1. Failure patterns

The beams were tested using a hydraulic device with a load capacity of 500 kN, with a linear variable differential transformer (LVDT) used to measure the deflection of each beam. Fig. 7 and Fig.8 shows the failure mode of normal beams and ferrocement beams respectively, where FC beams generally gave good load-bearing results and a better number of cracks than FC beams without plastic waste fibers, where the ferrocement beams with fiber content showed control over cracks despite their spread and greater number. Still, they were microcracks, unlike the cracks of the reference beams, which is consistent with what was stated by Erfan's group (Erfan, Elafandy, Mahran, & Said, 2021). In addition, plastic waste fibers act as a bridge to transfer loads from one side to the other and contribute to not expanding the crack width. The load causing the first crack was calculated for each sample, and it is known that mortar cracks are faster and less durable than normal concrete (Shaheen et al., 2023). However, this research showed that when the mortar was reinforced with (WWM) as an alternative to stirrups and (PET) fibers, it gave similar load-bearing capacity at the first crack in most beams.

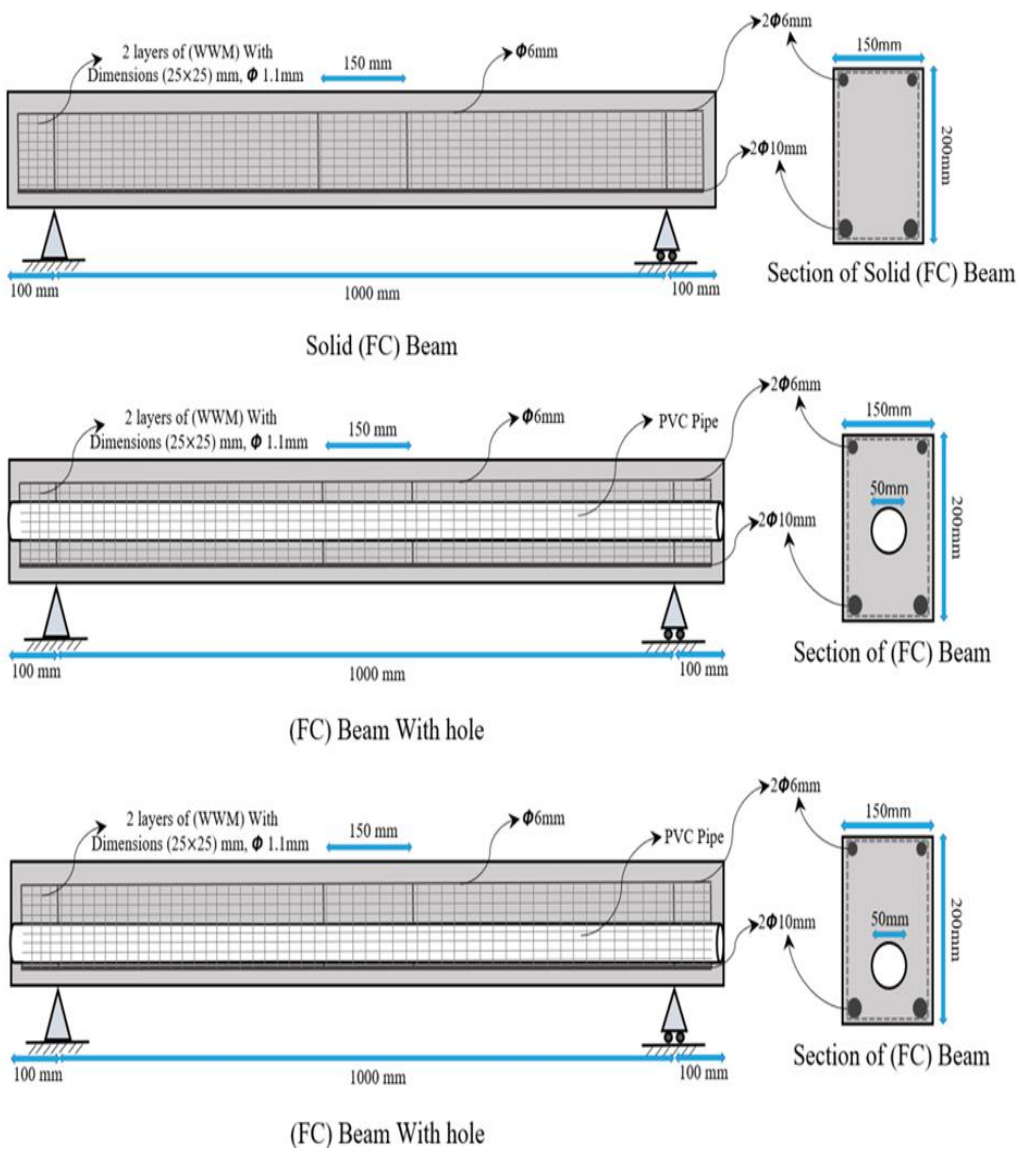

Fig. 6 Illustration of (FC)Beams.

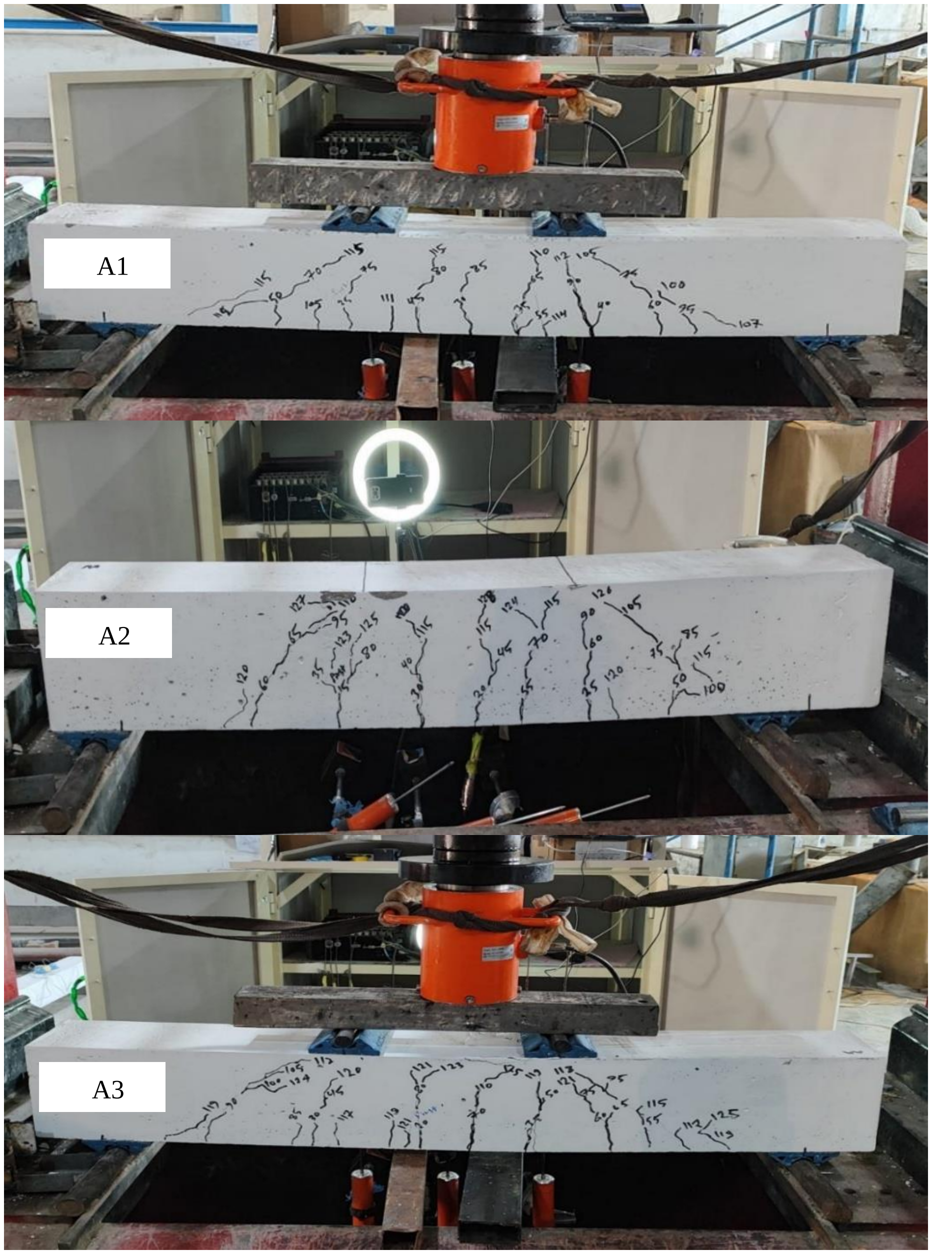

Fig. 7 Crack patterns in normal beams

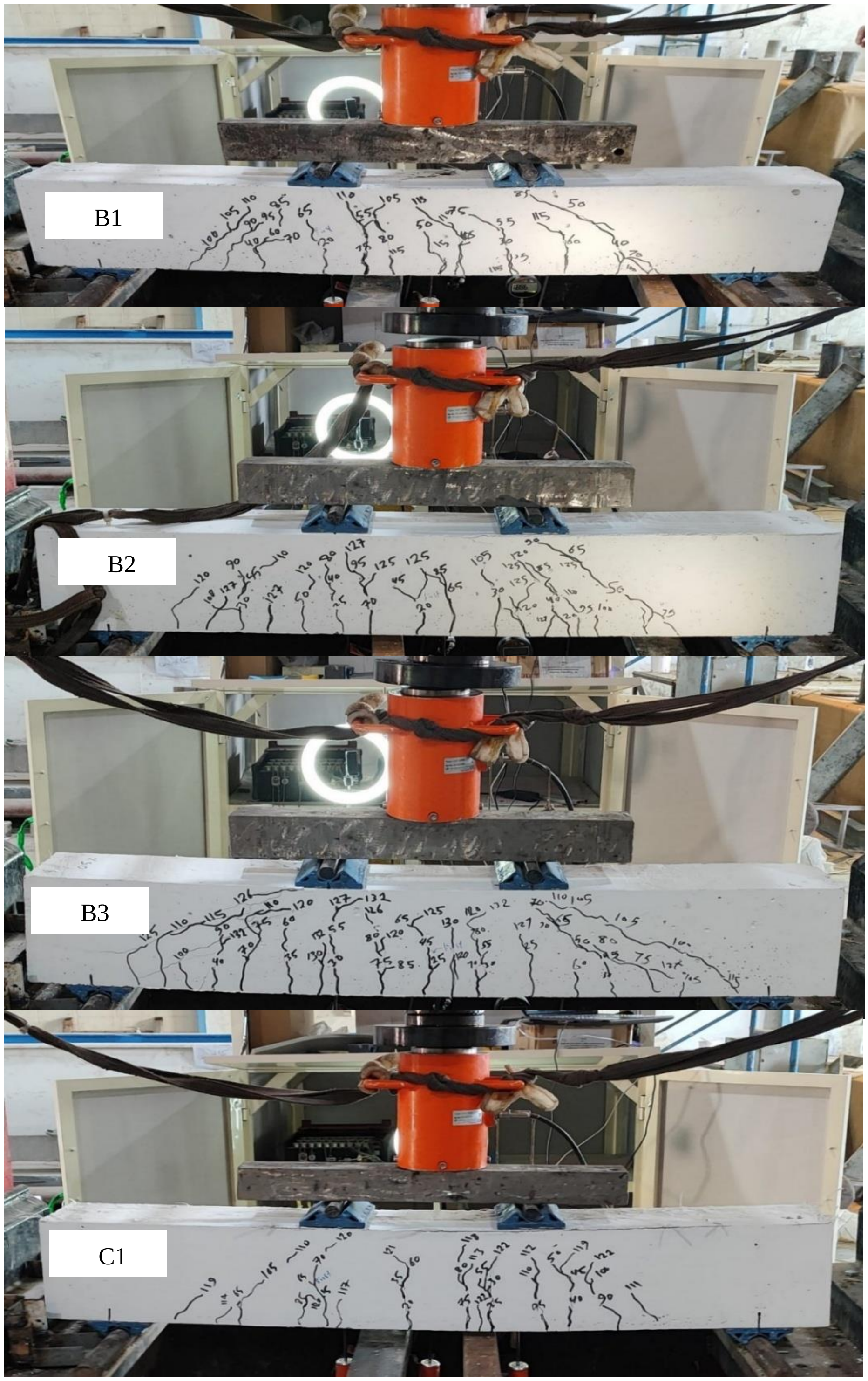

Fig. 7 a. Crack patterns in ferrocement beams

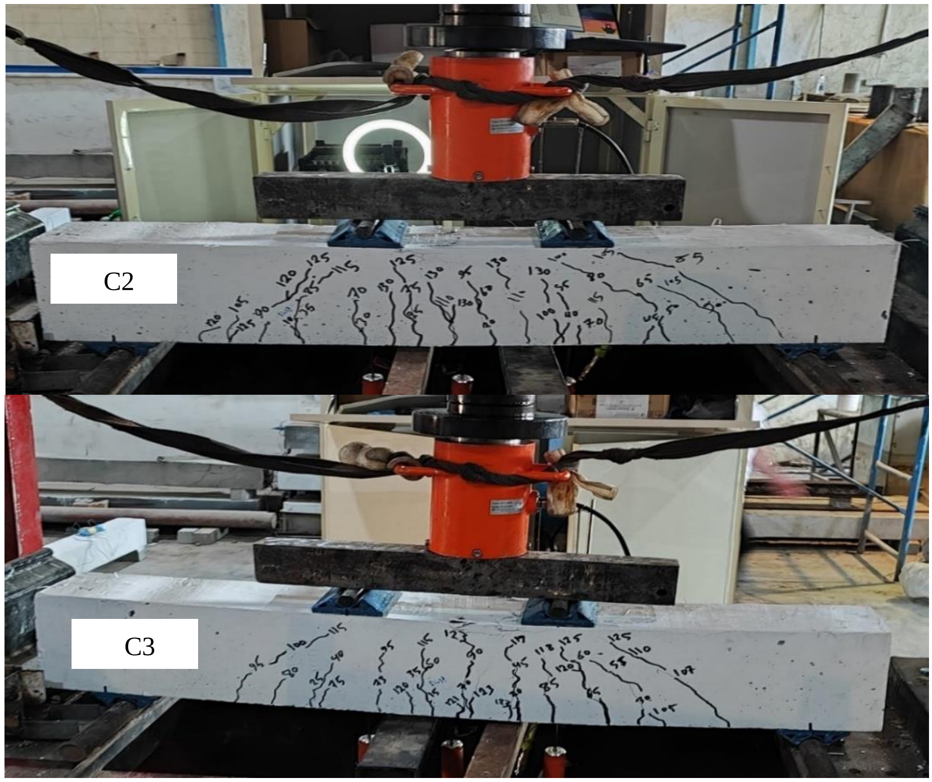

Fig. 7.b. Crack patterns in ferrocement beams

3.2. Effect of hole location on beams

3.2.1. Load-deflection at first crack

The beams were divided into three groups, each containing two beams with a hole, and compared with the solid beam from the same group. The results of the load and deflection at the first cracks were included in Table 2 to determine the percentage of the hole's effect on the beams' structural performance. The ferrocement beams had a cracking load resistance in beams (A2 and A3) that was 40% and 20% lower than beams (A1), respectively, while the deflection in beams (A2) was close to beams (A1), but the deflection increased in beams (A3) by 9.75%. In ferrocement beams containing 0.5% of (PET) fibers, the cracking load in beams (B2) was the same as in beams (B1), while in beams (B3), the cracking load improved by 25%, i.e. the location of the hole and the presence of (PET) fibers led to the improvement. As for the deflection, the deflection increased under the cracking load for beams (B2 and B3) by 13.16% and 15.78%, respectively. When the percentage of (PET) fibers increased to 1%, the beam (C2) cracking load decreased by 33%, than beam (C1). As for beam (C3), the cracking load was the same as in beam (C1), but the deflection was also less in the beam containing a hole in the neutral axis region than the one below it compared to the solid beam containing 1% of (PET) fibers by 5.88% and 129.41%, respectively. In general, it is noted that the effect of the hole was on the deflection, especially in the hole located at the bottom of the neutral axis region, where the deflection increased from the hole located in the neutral axis, and this is consistent with what was mentioned by the study accomplished by Jasim, Allawi, and Oukaili (2019).As for ferrocement beams containing (PET) fibers by 0.5%, the plastic fibers improved the resistance to cracking loads as they acted as a solid beam. This is because the fibers helped increase the bonding and stiffness between the fibers and the cement paste, but when the percentage of (PET) fibers increased to 1%, the effect was opposite, as mentioned by Gu and Ozbakkaloglu (2016).The resistance to cracking load and resistance to deflection decreased in general compared to all beams.

Table 2 – Effect of hole on load-deflection at the first crack.

Beam	P_{cr} (KN)	Change in P_{cr} (%)	Δ_{cr} (mm)	Change in Δ_{cr} (%)
A1	25	----	0.41	----
A2	15	-40	0.40	-2.44
A3	20	-20	0.45	9.75
B1	20	----	0.38	----
B2	20	0	0.43	13.16
B3	25	25	0.44	15.78
C1	15	----	0.17	----
C2	10	-33	0.18	5.88
C3	15	0	0.39	129.41

3.2.2. Ultimate load- deflection

The groups were divided as previously mentioned, as Table 3 shows the results of the maximum load and deflection, while Fig. 9 shows the relationship between the load and deflection for each group, These figures illustrate the behavior of beams from the beginning of load application to the failure stage, and all beams go through three stages: the first cracking stage, in which the ratio of increase in stress to strain is constant, which begins with load application and ends at the first cracking point. As for the second stage, it is the stage in which the behavior is elastic, which begins from the first crack to yielding, as the beam does not fail at this stage, but the cross-sectional stiffness decreases with a decrease in the elastic modulus, accompanied by an increase in the length and number of cracks with an increase in the deflection until the reinforcement reaches the yielding stage, and thus a change occurs in the curve during this stage because when the first crack occurs, the effective cross-sectional depth of the beam decreases. As for the third and final stage, which is known as the inelastic behavior stage, it begins from the yielding point to failure, as with the constant increase in the applied load, the deflection increases continuously until failure and collapse of the beam occurs. To put it another way, in order to attain the maximum toughness and ductility, the deflection of the beam should be as low as feasible at the highest loading level in the yield stage and as high as possible at the highest loading level likewise in the ultimate stage. Where the (A2) beams had a higher resistance by 10.41%, while the (A3) beams had a resistance but by 9.24% compared to the reference beam (A1). As for the ferrocement beams containing (PET) fibers by 0.5%, the beam with a hole below the neutral axis region had an increase in the maximum load by 14.86% compared to the reference beam. As for the ferrocement beams containing (PET) fibers by 1%, the increase in resistance due to the beam with a hole in the neutral axis region by 7.07%. As for the deflection, it was found that all beams compared to the reference beam for each group, it was noted that the beam with a hole in the bottom of the neutral axis region had a higher deflection than the beam with a hole in the neutral axis region. These results are consistent with what Gatia Abtan and AbdulJabbar (2019) obtained. Gatia Abtan and AbdulJabbar (2019) have concluded that any void in the beam negatively affects the behavior of the beam, but the failure level does not always pass through the hole and the deflection in the beam containing a hole in the tension area is greater than that in others.

Table 3 – Effect of hole on Ultimate load-deflection.

Beam	P_u (KN)	Change in P_u (%)	Δ_u (mm)	Change in Δ_u (%)
A1	115.22	----	11.28	----
A2	127.21	10.41	12.66	12.23
A3	125.87	9.24	12.96	14.89
B1	116.55	----	10.36	----
B2	129.20	10.85	12.55	21.1

B3	133.87	14.86	12.12	16.98
C1	122.54	----	9.49	----
C2	131.20	7.07	8.61	-9.27
C3	125.21	2.18	10.05	5.90

3.3. Effect of (PET) fiber ratios on beam performance

3.3.1 Load-deflection at first crack

The load and deflection results at the first crack for Groups A, B, and C beams are listed in Tables 4, 5, and 6, respectively. The results for the solid beams showed that the ferrocement beams containing 0.5% and 1% PET fibers had a lower cracking load than those without these fibers. Still, the result was the opposite in deflection, as the fibers in the beams at a rate of 0.5% and 1% helped reduce the deflection by 7.32% and 58.54%, respectively. As for the beam with a hole in the neutral axis region, the fibers improved the cracking load by 33.33% for the beam containing 0.5% plastic fibers, while the cracking load for the beam containing 1% fibers was 33.33% lower than the reference beam, these results are consistent with the findings of Fraternali's and Kim's groups (Fraternali, Ciancia, Chechile, Rizzano, Feo, & Incarnato, 2011; Kim, Yi, Kim, Kim, & Song, 2010) reported that using plastic fibers at a rate of 0.5% to less than 1% delayed the appearance of cracks while increasing the load resistance. While the plastic fibers contributed by using 1% of them to reduce the deflection by 55%, unlike the beam containing 0.5% of the fibers, the deflection increased by 7.5% compared to the reference beam. As for the ferrocement beams that have an opening at the bottom of the neutral axis area, it was also in terms of load, improving the percentage of 0.5% of the fibers by 25% and reducing the cracking load by 1% by 25%, while in terms of deflection, the contribution was in addition to the beams that have 1% of the plastic fibers, as they reduced the deflection by 13.33%, as they contributed to reducing the deflection, as the deflection decreased due to the contribution of the fibers that helped in increasing the bonding during the first cracking stage, and this is consistent with what Jamal and his team concluded. They mentioned that the tensile strength increases with increasing the percentage of plastic fibers at the same load level (Khatib, Jahami, Elkordi, Abdelgader, & Sonebi, 2020).

Table 4 – Effect of (PET) fibers on load-deflection at the first crack for solid beams.

Beam	P_{cr} (kN)	Change in P_{cr} (%)	Δ_{cr} (mm)	Change in Δ_{cr} (%)
A1	25	----	0.41	----
B1	20	-20	0.38	-7.32
C1	15	-40	0.17	-58.54

Table 5 – Effect of (PET) fibers on load-deflection at the first crack for beams that have a hole in the neutral axis.

Beam	P_{cr} (kN)	Change in P_{cr} (%)	Δ_{cr} (mm)	Change in Δ_{cr} (%)
A2	15	----	0.40	----
B2	20	33.33	0.43	7.5
C2	10	-33.33	0.18	-55

Table 6 – Effect of (PET) fibers on load-deflection at the first crack for beams that have a hole under the neutral axis.

Beam	P_{cr} (kN)	Change in P_{cr} (%)	Δ_{cr} (mm)	Change in Δ_{cr} (%)
A3	20	----	0.45	----
B3	25	25	0.44	-2.22
C3	15	-25	0.39	-13.33

3.3.2. Ultimate load- deflection

The results in Table 7, 8, 9, and Fig. 10 indicate the role of PET fibers in each group in increasing the load resistance that leads to strengthening the beams, as the solid ferrocement beams containing plastic fibers showed an improvement in the maximum load in the beam with a percentage of 1% PET fibers by 6.35%, which was higher than the load of the beam with 0.5% PET fibers, which was close to the load of the reference beam. As for the deflection, both beams contributed to reducing the deflection, but the beam with a 1% fiber content also reduced the deflection by 15.87%, while the beam with a 0.5% content had a reduction rate of 8.16%. As for the beams with an opening in the neutral axis area, beam C2 witnessed an increase in load resistance higher than beam B2 by 3.14% compared to the reference beam for this group. As for the deflection, beam B2 was very close to the deflection of beam A2, as the deflection reduction rate was 0.87 %. As for the C2 beam, it had the largest reduction ratio, as it reduced the deflection by 31.99%. As for the beams that had an opening at the bottom of the neutral axis area, the resistance to the load was next to the B3 beam, as the load resistance increased by 6.36%. As for the C3 beam, the load resistance was very close to the reference beam load but less by 0.52%. As for the deflection, the C3 beam was reduced by 22.45% more than the B3 beam, which had a reduction ratio of 6.48% compared to the reference beam of the same group. In general, the maximum load resistance for all ferrocement beams did not exceed 7%. As for the deflection, the beams with a percentage of 1% (PET) fibers reduced the deflection more than the beams with 0.5% of fibers, as these fibers work to fill the cracks and delay their formation. Hence, these cracks are precise in addition to their work in delaying the transfer of loads and their work as a bridge to transfer these loads. This is consistent with a previous study conducted by Rahimi and Irwan teams (Rahimi & Kesler, 1979; Irwan, Asyraf, Othman, Koh, Aeslina, Annas, &Faisal, 2014).

Table 7 – Effect of (PET) fibers on Ultimate load-deflection for solid beams.

Beam	P_u (kN)	Change in P_u (%)	Δ_u (mm)	Change in Δ_u (%)
A1	115.22	----	11.28	----
B1	116.55	1.15	10.36	-8.16
C1	122.54	6.35	9.49	-15.87

Table 8 – Effect of (PET) fibers on Ultimate load-deflection for beams that have a hole in the neutral axis.

Beam	P_u (kN)	Change in P_u (%)	Δ_u (mm)	Change in Δ_u (%)
A2	127.21	----	12.66	----
B2	129.20	1.56	12.55	-0.87
C2	131.20	3.14	8.61	-31.99

Table 9 – Effect of (PET) fibers on Ultimate load-deflection for beams that have a hole under the neutral axis.

Beam	P_{cr} (kN)	Change in P_{cr} (%)	Δ_{cr} (mm)	Change in Δ_{cr} (%)
A3	125.87	----	12.96	----
B3	133.87	6.36	12.12	-6.48
C3	125.21	-0.52	10.05	-22.45

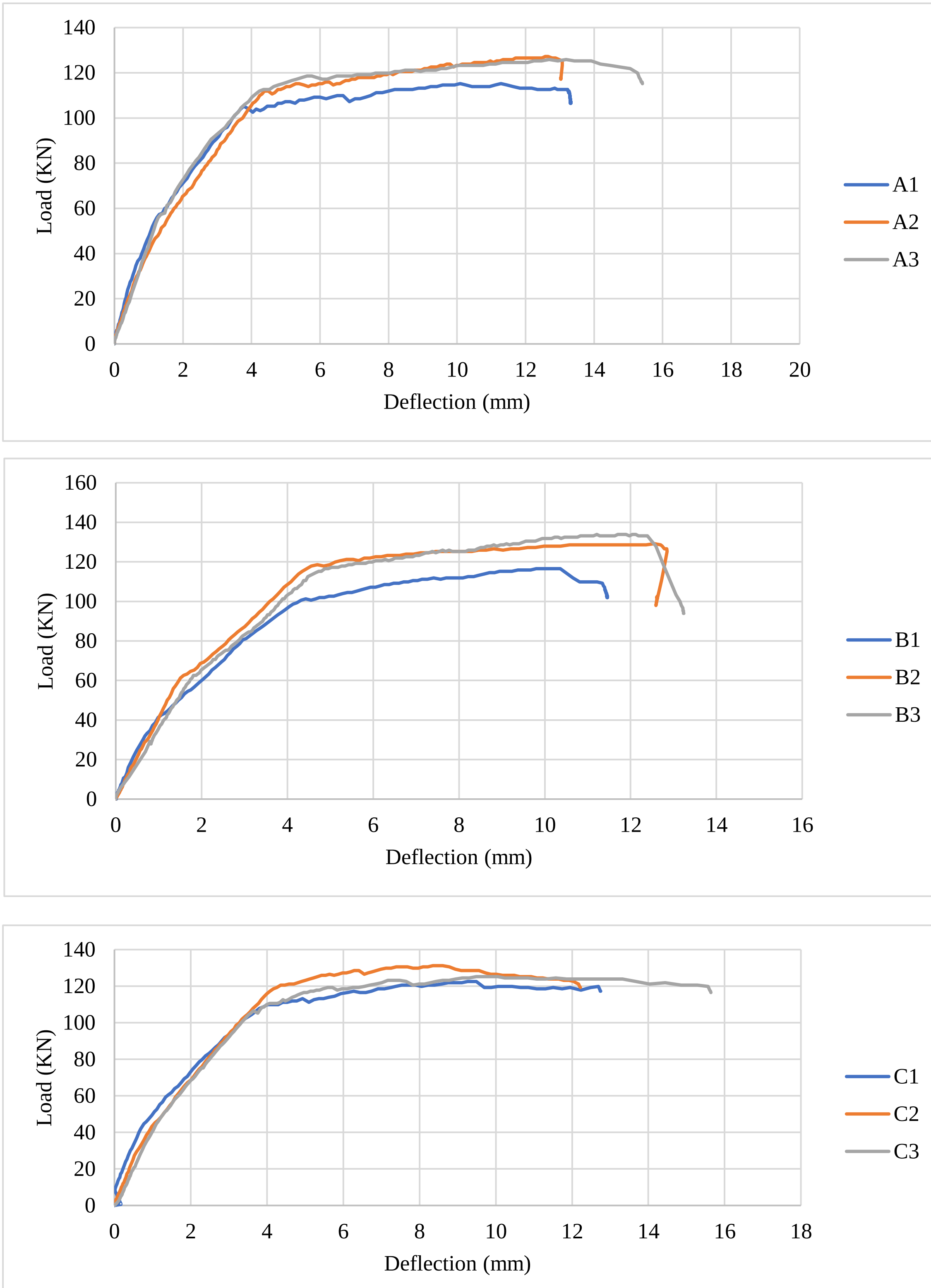

Fig. 9 The relationship between load and deflection showing the effect of the hole

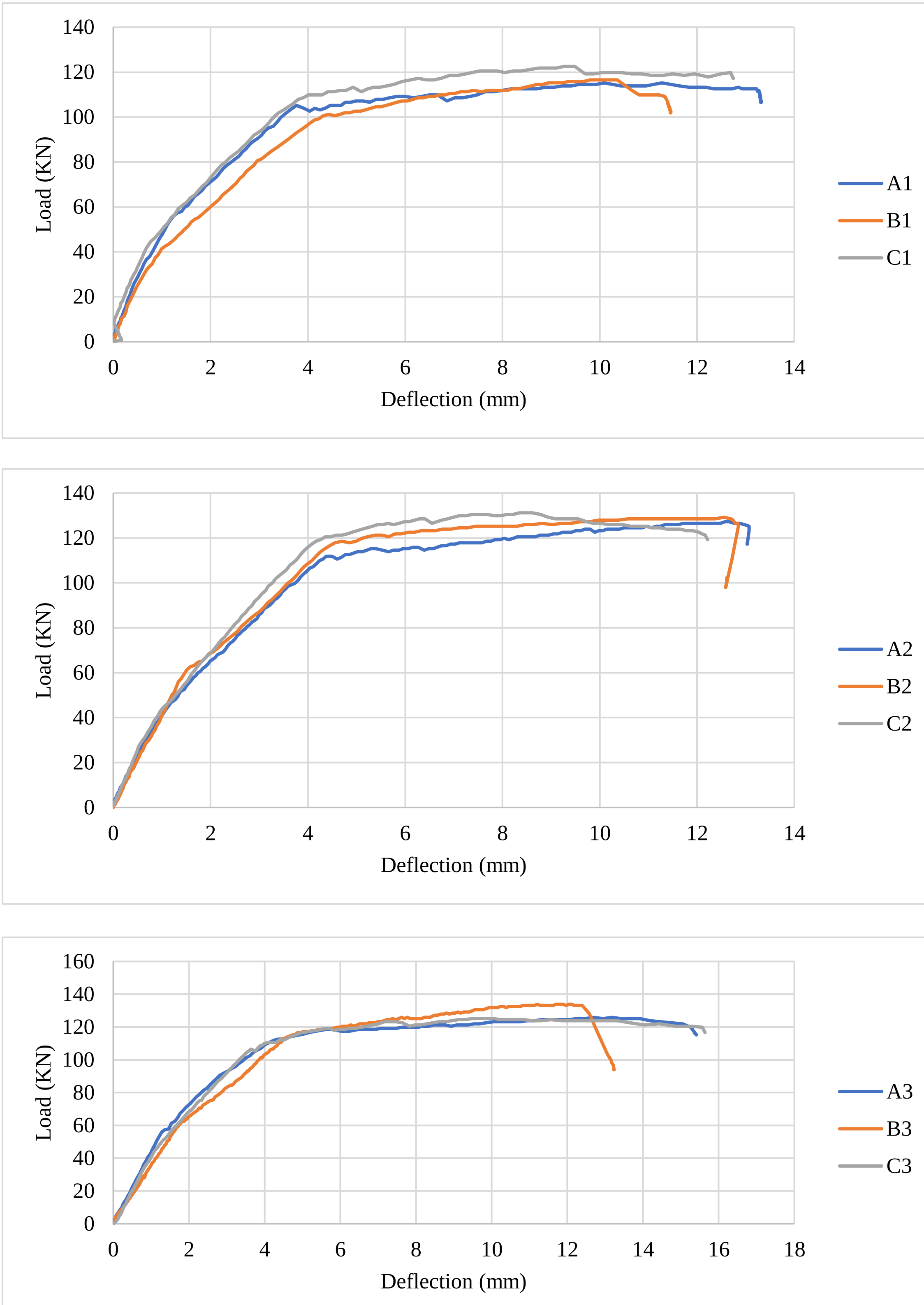

Fig. 10 The relationship between load and deflection showing the effect of the (PET) Fibers

3.4. Toughness

Toughness can be defined as the ability of the structure to absorb energy and resist plastic deformation, as toughness is related to the area under the load and deflection curve from the zero-load stage to the ultimate load, (Hamad & Sldozian, 2019). The area under the load and deflection curve was calculated according to ASTM C 1018 (ASTM C 1018, 1997) specifications, as the area was calculated using Excel and AutoCAD programs, and the results were identical, as shown in Fig. 11 of the toughness values for the beams, as the addition of (PET) fibers led to improving the toughness of the solid ferrocement beams by a percentage ranging from 9.72% to 415.38%, and these results are consistent with the study of Al-Hadithi and Ahmed (Al-Hadithi & Ahmed, 2018), as the increase in plastic fibers led to an increase in energy absorption (Toughness). This is consistent with what was mentioned by Cao and his team (Cao, Li, Brouwers, Sluijsmans, & Yu, 2019). The ferrocement beams containing an opening had a toughness improvement rate of 8.60% to 351.73%, compared with the ferrocement beams without fibers (PET).

3.5. Stiffness

Stiffness can be defined as a measure of the resistance of a beam to deformation in response to an applied load. In other words, a structure can resist bending, stretching, or twisting, i.e., the force required to achieve a certain deformation on the material. The results shown in Fig. 12 indicate that the beam (FC-N-1%) recorded the highest stiffness result (15.24 kN/mm) due to the percentage of plastic waste fibers used, which improved the stiffness value. As for the ferrocement beam, stiffness improved, and the stiffness values ranged from 9.71 kN/mm to 12.91 kN/mm.

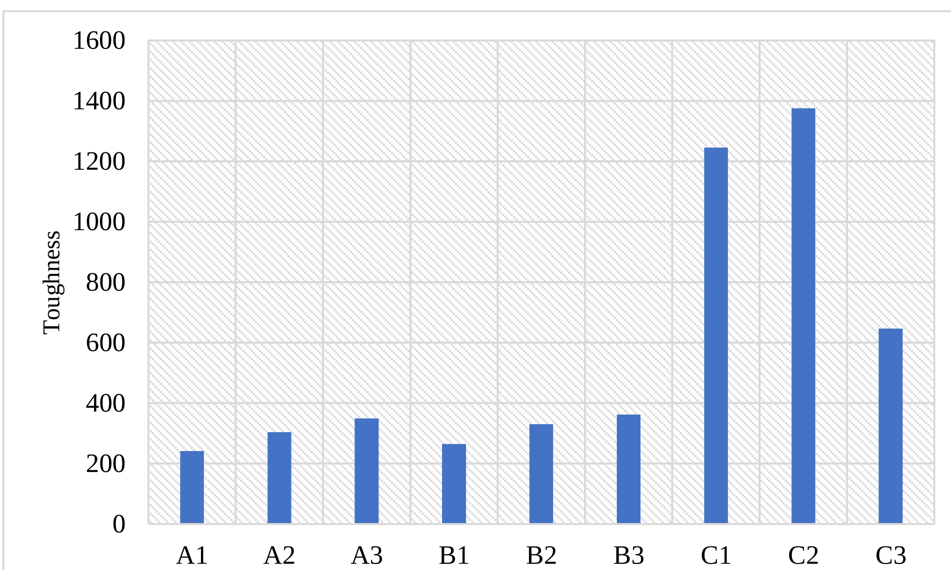

Fig. 11 Toughness

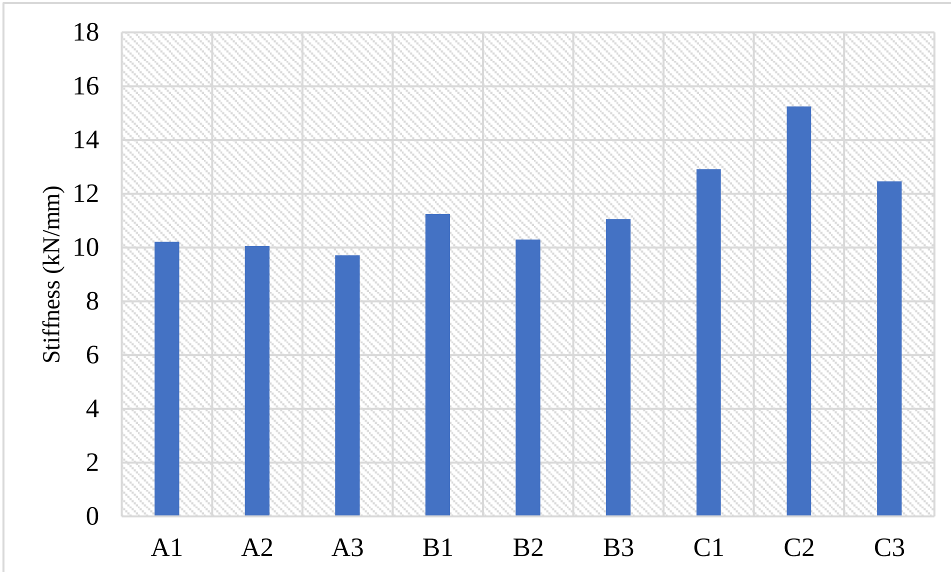

Fig. 12 Stiffness

4. Conclusion

1. The use of ferrocement reinforced with two layers of welded wire mesh as an alternative to stirrups demonstrated satisfactory behavior and load resistance concerning the cracking load. Most of the ferrocement beams experienced the same load at the point of first cracking, with a variation in cracking load of ±10%.
2. The number of cracks in the ferrocement beams containing plastic waste fibers was greater than in the reference beams; however, the wire mesh and the remaining plastic fibers effectively controlled these cracks. The plastic fibers prevented the cracks from spreading in different directions and reduced their width due to the strong bonding between the cement paste and the well-distributed, non-agglomerated plastic fibers within the beams.
3. In ferrocement beams, including those with longitudinal holes smaller than 0.4D, plastic fibers enhance the ultimate load resistance and effectively reduce deflection at maximum load.
4. Incorporating plastic waste fibers into ferrocement beams improves their performance and support environmental sustainability by repurposing plastic waste resources. This aligns with efforts to reduce the environmental impact of building materials and to utilize environmentally friendly construction techniques worldwide. This type of research can be expanded by combining various plastics to produce composite fibers that offer enhanced strength, durability, and environmental benefits. Additionally, different shapes and sizes of longitudinal holes can be created to improve mechanical properties and crack resistance.

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