Investigation of Maximum Mid-Span Displacement and Reaction Forces in Fiber-reinforced Concrete Beams subjected to Impact

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ABSTRACT

Self-Compacting Fiber-Reinforced Concrete (SCFRC) is a specialized type of concrete that combines the properties of Self-Compacting Concrete (SCC) with the addition of fibers for reinforcement. SCFRC is designed to have excellent flowability and self-leveling characteristics while providing enhanced tensile strength, ductility, and crack resistance. This paper presents a discussion on the topic of SCFRC and the impact load behavior of SCFRC beams reinforced with Waste Plastic Fibers (WPFs). A comparison with reinforced concrete beams without fibers is also conducted. This study aims to predict the maximum mid-span displacement and the maximum reaction force of the fiber concrete beams under impact load. Twelve beams that represent the total adopted parameters were tested under impact loading. The beams were divided into three main groups according to the longitudinal steel ratio. The steel ratio was varied by using steel bars of 10, 8, and 6 mm diameter, with PET waste fibers with different volume ratios V_f% of 0, 0.5, 0.75, and 1%. The results showed that the use of beams is reinforced with ρ_{max}, $\rho_{max} > \rho > \rho_{min}$, and ρ_{min} having reduced maximum deflection by 24.23%, 35.9%, and 46.28%, respectively, when using WPFs with a volumetric value of 1%. This paper also covers work steps, model details, and the tests that were carried out on the specimens, which were made from materials available in local markets.

Keywords-self-compacting reinforced concrete; waste plastic fibers; impact load

I. INTRODUCTION

The behavior of reinforced concrete under impact is an active area of research that continues to be explored. While significant progress has been made in understanding the response of concrete structures to static loads, the dynamic behavior of reinforced concrete subjected to impact loads is still a challenging topic [1]. Examples include reinforced concrete structures designed to resist accidental loading scenarios, such as falling rock impact, vehicle or ship collisions with buildings, bridges, or offshore facilities; and structures that are used in high-threat or high-hazard applications, such as military fortification structures or nuclear facilities. Several factors contribute to the complexity of studying the impact behavior in reinforced concrete [2]. These factors include the heterogeneous nature of concrete, the presence of reinforcement, the dynamic response of different materials, and the variability in impact loading conditions. Additionally, the behavior can vary depending on factors like material composition, mix design, reinforcement details, and specimen geometry [3]. Research and experimentation have been carried out to assess the reaction of continuous steel-reinforced, Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) beams under low-velocity loading. In order to thoroughly assess the behavior of UHPFRC beams subjected to low-velocity loads, these investigations combine experimental testing, numerical simulations, and analytical modeling techniques [4]. The inertia force mostly resists the impact force due to the impact loading's brief duration. Owing to the dynamic equilibrium that is created as a result, the RC member's bending moment and internal force are more complex [5–7]. The most commonly used design codes for structures that specialize in impact loading, like ACI 349-13 [8] and UFC 340-02 [9], are only applicable to special structures like nuclear power plants and military installations, and their primary concerns are focused on high-velocity impact loading, like aircraft impact and explosion. This suggests that the application of these rules to general social infrastructure, such as bridges and buildings, is restricted because these structures are more likely to be exposed to low-velocity impact loading than high-velocity impact loading, including rock falls, cars, and ship accidents. In contrast to high-velocity impact phenomena, where local damage is the primary indicator of structural failure, when structures are subjected to low-velocity impact loads, global reactions, such as displacement and rotation, are the prominent markers of structural failure. However, there is currently no precise technology available to assess and control the overall behavior of concrete members under low-velocity impact loads [10].

The second most frequently dumped plastic material, behind polythene, is polythene terephthalate (PET) [11, 12]. PET, one of the most produced and commonly used plastics in the world, is utilized to package soft drinks, drinking water, food, and other consumer items [13, 14]. Plastic waste poses several environmental challenges. Plastics are not easily biodegradable and can persist in the environment for hundreds of years, leading to long-term pollution. Improper disposal of plastic waste, such as littering or improper landfilling, can result in plastic debris ending up in the environment. Plastic waste also can clog drainage systems, leading to flooding in urban areas, or contribute to the formation of microplastics, which are small particles that can accumulate in ecosystems and have detrimental effects on organisms. Plastic waste recycling in construction, i.e. the use of shredded plastic waste as aggregates or plastic fibers in the production of concrete is a well-known method of recycling. This approach aims to reduce the environmental impact of plastic waste while incorporating its beneficial properties into construction materials. However, it is important to note that the exact proportions and types of plastic used in concrete mixtures can vary depending on the desired properties and structure requirements. SCFRC finds applications in a wide range of construction projects, including bridges, tunnels, high-rise buildings, precast elements, and infrastructure projects. It is commonly used in structural elements, like beams, columns, slabs, and walls, where improved crack control and enhanced durability are critical. Overall, recycling plastic waste in construction, particularly in the production of SCFRC, can contribute to sustainable building practices, reduce the environmental impact of plastic waste, and promote the efficient use of resources [15, 16].

This study investigated the effect of the ratio of plastic fibers incorporated in SCFRC mix design. The behavior of concrete beams under impact load was studied while varying this ratio. The main goals of this study are to improve the performance of SCFRC mix designs and create design standards for structures using SCFRC beams under low-velocity loading conditions. This study offers important insights on how to improve the behavior of SCFRC beams, making them better suited for structural applications where low-velocity loads are an important factor. SCC provides numerous benefits in contrast to conventional concrete. These advantages consist of enhanced construction quality, expedited construction process, cost reduction, improved quality of in-place concrete, even in challenging casting conditions, and decreased occurrences of accidents, noise, and vibrations. Additionally, it also facilitates the achievement of a superior surface quality [17]. As far as is known, no previous research has been conducted on self-compacting reinforced concrete beams containing plastic waste fibers under impact loads, representing a considerable gap in the literature. This research study significantly advances the comprehension of the structural behavior of SCC beams upon the inclusion of plastic fibers, with a specific focus on deflection and reaction characteristics.

II. EXPEREMENTAL WORK

A. *Materials*

Ordinary Portland Cement (Al-Mass), which met Iraqi requirements (IQS No.5/ 2019) [18], was the cement utilized in this project (see Table I). Additionally, coarse aggregates (with a particle size of up to 10 mm) and fine aggregates, which comply with the Iraqi standard specification (I.Q.S.) No.45/84 (see Table II) [19] were utilized. Tap water was used for mixing and curing. The additives employed in this research included EPSILONE I 21 superplasticizer and High Range Water Reducing/Superplasticizer, confirming to ASTM C 494 Type G and F [20]. Silica Fume (SF) Type Mega Add MS(D) with a specific gravity of 2.2 was used in the SCC mixes. The United Arab Emirates (UAE) produces SF, according to ASTM C1240 [21]. Waste Plastic Fiber (WPFs) with 3 mm width and 30 mm length that were produced by a paper shredded machine (See Table III) were also utilized.

TABLE I. PHYSICAL CEMENT COMPOSITION PROPERTIES

Physical properties	Result	Limit No.5/2019
Fineness using the Blain method (m^2/kg)	361	≥ 250
Time of initial setting (min)	160	≥ 45
Time of Final setting (hr)	260	≤ 10
Soundness (mm)	1	≤ 10
Autoclave %	0.1	≤ 0.8%
The compressive strength of mortar		
2 days (MPa)	20	≥ 10
28 days (MPa)	37	≥ 32.5

TABLE II. COARSE AND FINE AGGREGATES SIEVE ANALYSIS

Sieve Size (mm)	Passing %	Iraqi specification No. 45/1984 limit
Coarse aggregates		
20	100	100
14	100	90-100
10	82.9	50-85
5	8	0-10
Fine aggregates		
10	100	100
4.75	97	90-100
2.36	81	75-100
1.18	68	55-90
0.6	43	35-55
0.3	9	8-30
0.15	2	0-10

TABLE III. DIMENSIONS AND PHYSICAL PROPERTIES OF WPF

Property	Description
Aspect Ratio	28.025
Tensile Strength (MPa)	105
Density (kg/m^3)	1.1
Water absorption	0.00

B. Mix Design

The specifics of the experimental mixtures are presented in Table IV including the amount of coarse aggregates, plasticizers, and fillers according to the limitations indicated in the [22].

TABLE IV. MIX PROPORTIONS FOR SCC (kg/m^3).

Mix	Fiber content%	Cement	Sand	Coarse aggregates	Water	SF	Superplasticizers
MO*	0	475	950	700	169	50	13
MA*	0.5	475	950	700	169	50	13
MB*	0.75	475	950	700	169	50	13
MC*	1	475	950	700	169	50	13

*MO (mix class 0 with 0% fiber content), MA (mix class A with 0.5% fiber content), MB (mix class B with 0.75% fiber content), *MC (Mix class C with 1% fiber content).

C. Testsing Procedure

1) Compressive Strength and Static Modulus of Elasticity Tests

Three standard cylindrical specimens with diameter and height measurements of 150 and 300 mm, respectively, were used for compressive strength tests at a rate of 5.30 KN/s, subjected to ASTM C39-05 [23] and for static modulus of elasticity tests subjected to the ASTM C469-02. [24] It is possible to determine Young's modulus in a compressive test machine at a loading rate of 5.3 kN/s by encircling the sample with a 150 mm diameter compressor-meter ring and measuring the longitudinal axis of the sample's deformation through compression via a dial gauge with an accuracy of 0.002 mm. The value of elastic modulus can be established by:

$$Ec = \frac{S2 - S1}{\mathcal{E}2 - 0.00005} \quad (1)$$

where E_c is the static modulus of elasticity (MPa), S is the stress corresponding to $\mathcal{E}$ (MPa), $\mathcal{E}1$ is the longitudinal strain of 0.00005, and $S2$ is the 40% of the ultimate stress.

2) Splitting Tensile Strength Test

This examination was conducted in accordance with ASTM C496-11 [25]. After 28 days of curing, it was carried out on 150×300 cylindrical samples. The tests were conducted in the same compression strength device at a rate of 0.94 kN/s.

D. Testing Program for Reinforced Concrete Beams

The beams were designed with shear capacity greater than flexural capacity, according to ACI 318-19code [26]. The dimensions of the proposed model were 1500 mm length, 100 mm width, and 150 mm depth. Since 12 wooden molds were created for casting the aforementioned beams, the molds were designed with separate parts to allow for easy editing of the models after solidification. Rebars with diameters of 6, 8, 10 mm were used in the tension zone and two with diameters of 6 mm were used in the compression zone. Shear reinforcement (stirrups) with a diameter of 6 mm were utilized. All sides of the net cover were 20 mm thick. Figures 1-2 depict the specimen's geometry and cross-section details.

Fig. 1. Geometry of the specimen and cross-section data.

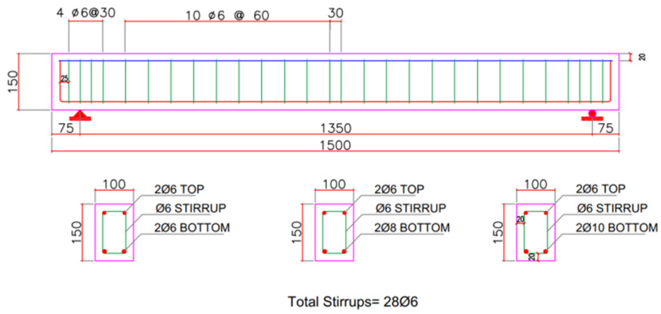

Fig. 2. Details of reinforced concrete beams.

E. Impact Loading Test

The tests were carried out at the University of Technology's Laboratory. The same procedure was followed to test all specimens. The beam was supported by the testing rig and the released dropped mass was led by gravity without any other external force. The specimens were placed in the testing frame with their finished faces up. The falling mass was dropped once, and the deflection was measured. The following steps summarize the test procedure:

- All of the equipment and sensors were properly positioned.
- The beam was securely fastened to the rigid supporting frame.
- The two load cells are located on the bottom face of the beam.
- The laser sensor was positioned beneath the center of the beam.
- The projectile was held in place by a cable.
- The cable was withdrawn and left to allow for a free fall.
- The impacted falls vertically to the sample midspan using a steel tube.

Figure 3 depicts the stages of beam testing, the setup, and the support system for the impact test. The reinforced concrete beam was precisely positioned in the center of the testing frame. A circular-section tube was used as a vertical guide for the falling mass, ensuring a mid-span impact. The impact body weight was constant at 24.450 kg. The impact body was shaped like a cylinder and was made up of two parts: a solid steel ball with a diameter of 100 mm and a weight of 4.450 kg at the bottom to deliver the hammer's impact energy to the sample and a steel cylinder with a height of 330 mm and a diameter of 100 mm at the top to deliver the hammer's impact energy to the sample. The height distance from the impact body's face to the beam surface was constant at 2.1 m for all samples. The total applied dropped mass was equal to the combined mass of the solid steel ball and steel cylinder.

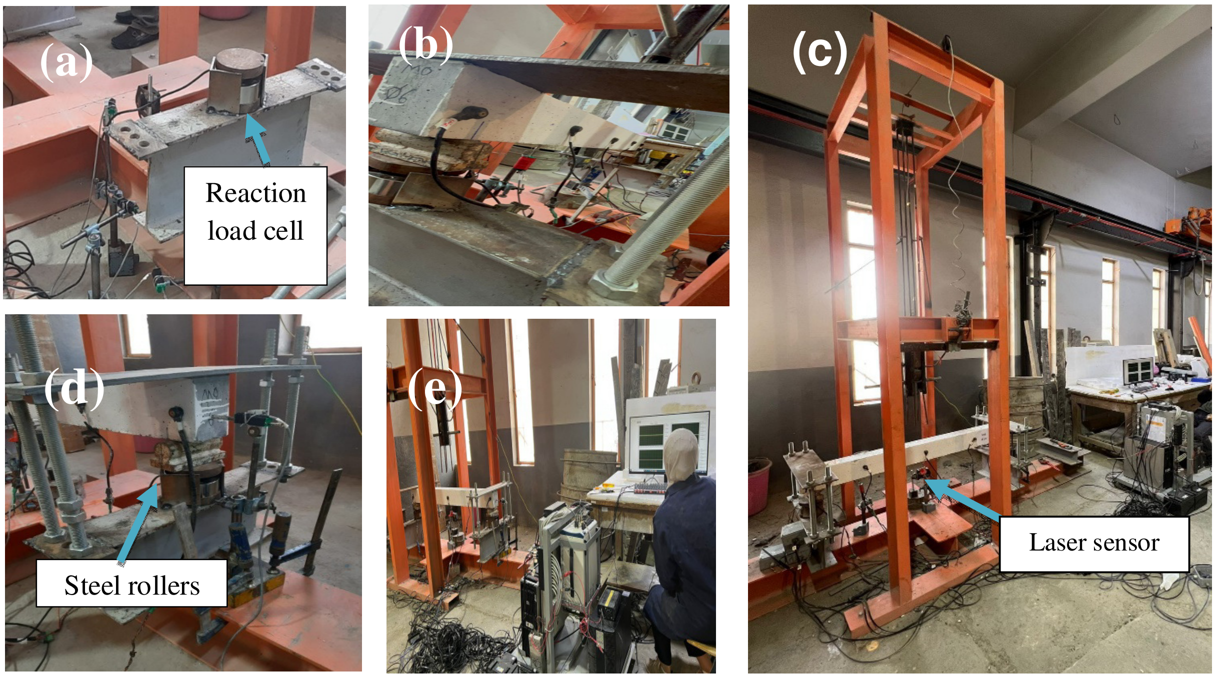

Fig. 3. Instruments used for impact testing.

III. EXPEREMENTAL RESULTS AND DISCUSSION

A. *Compressive Strength*

Table V shows the impact of the increase in the PET ratio in the concrete mixture on compressive strength. The experiment was carried out on samples at the age of 28 days with different PET ratios. The results show that the increase in the ratio of fiber increases the compressive strength up to 0.75% This improvement can be attributed to the ability of WPFS to lessen these tensions, bear the stresses, and bridge the cracks. When microscopic cracks develop in the bonding material (matrix), the fibers in the area around the cracks work to hinder the development of the cracks and prevent them from spreading. This causes the cracks to move in a zigzag pattern, requiring more energy to keep spreading and high pressures to collapse with different fiber content [27-29]. Then any increase in the proportion results in a decrease in compressive strength [30, 31]. This decrease was caused by the increase in WPF volume ratios, since it led to an uneven distribution of fibers in the concrete mix, which in turn led to fiber gathering and clumping together. Air gaps were build up beneath the PF as a consequence of the cement paste's declining homogeneity and adhesion to fiber surfaces [32].

B. *Static Modulus of Elasticity Test*

Adding WPFs to concrete mixture can have a significant impact on the modulus of elasticity of concrete. Plastic fibers, when incorporated into a concrete mixture, can enhance the mechanical properties of the resulting material. The addition of plastic fibers can increase the tensile strength and ductility of concrete, as well as improve its resistance to cracking and shrinkage. Consequently, this can lead to a raise in the modulus of elasticity. [33]. Table V displays the influence of the increase in the PET ratio in the concrete mixture on the modulus of elasticity. The results also indicate that the raise in the ratio of fiber increases the modulus of elasticity up to 0.75%. The bond strength between the fibers and the concrete mix has been enhanced by the close proximity and the short gaps between the fibers, the fibers obstruction of the cracks' growth and bridging, and the resistance to stresses. The modulus of elasticity begins to decline but still remains higher than that of the reference mix. This decline was caused by the fibers' erratic distribution, which made the fibers to aggregate, weaken the link between the fibers and the mix, and increase the air gaps beneath the fibers. In addition to the fact that plastic fibers have a lower modulus of elasticity than concrete at advanced ages, adding too much fiber content to concrete weakens the structure and lowers its modulus of elasticity.

TABLE V. PERCENTAGE INCREASE IN COMPRESSION STRENGTH, MODULUS OF ELASTICITY AND SPLITTING STRENGTH COMPARED TO PET RATIO

Mix	Fiber content%	Compressive strength at 28 days (MPa)	Increment (%)	Modulus of elasticity (GPa)	Increment (%)	Splitting strength ft (MPa)	Increment (%)
MO	0	48.8	0	31.4832	0	4. 806	0
MA	0.5	50.6	3.688	32.4131	2.9536	5. 485	14.128
MB	0.75	54.2	11.065	33.0524	4.9842	5.908	22.929
MC	1	52.7	7.991	32.7211	3.9319	5.722	19.059

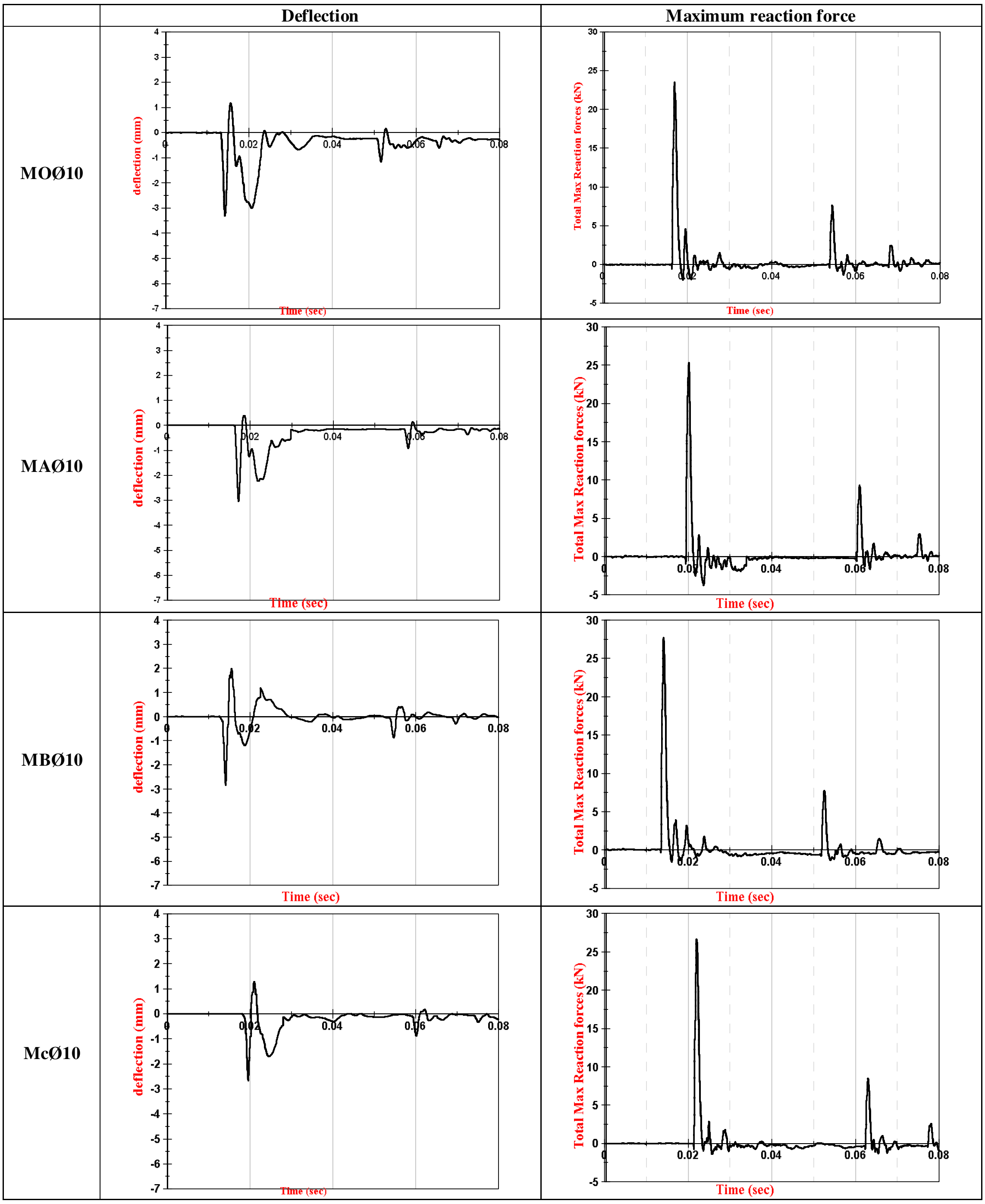

Fig. 4. Deflection time history and total maximum reaction force for the first group (ρ_{max}).

C. Splitting Strength

Table V shows the results of splitting tests for tensile strength for all concrete mixtures. The addition of WPFs to concrete mixes resulted in an increase in the compared tensile strength [34]. Adding fibers at a volume ratio of 0.5–0.75% demonstrated the highest increase in tensile strength. However, when the volumetric ratios of fibers exceeded 1%, the splitting tensile strength started to decrease due to the irregular fiber distribution, fiber agglomeration, and increased air voids. Despite the decrease, the fiber-containing concrete still had a higher tensile strength than the reference mix. In the reference mix, the failure mode after the initiation of cracks was the splitting of the cylinder into two parts. However, in the fiber-containing concrete, there was no sudden separation into two parts. Instead, the concrete cylinder exhibited resistance, and the cracks continued to develop and spread. This behavior persisted even under increasing tensile strength due to overloading until the ultimate failure was reached. Figure 5 provides a visual representation of this phenomenon.

Fig. 5. Failure mode of concrete cylinders under splitting strength.

D. Impact Loading Testing

1) Deflection Time-History

Figures 4, 6, 7 illustrate the representative time history responses of deflection. The shapes of the time histories of deflection were similar in reinforced concrete samples with the same diameter of reinforcement. It can be concluded that when the reinforcement ratio remained constant, increasing the proportion of plastic fibers clearly reduced both maximum deflection and residual deflection values. This means that the addition of these fibers increased the ductility of concrete beams made of SCC and containing WPFs. The factors mentioned above apply to the role of WPFs in enhancing ductility, they are uniformly distributed within the structure of the concrete mixture, augmenting homogeneity and reducing the amount of voids therein while also making the concrete body more cohesive and hard. When microcracks start to emerge within the matrix, WPFs attempt to stop their spread in the surrounding region by regulating their growth. Therefore, the cracking route becomes winded, requiring more energy to continue. When beams are subjected to impact load, fibers aid in minimizing deformations and excessive bending. Consequently, the elasticity of SCC containing WPFs was improved by the fiber addition.

2) Time Histories of Total Maximum Reaction Force

Figures 4, 6, 7 represent the time histories of total maximum reaction force. The shapes of the time histories of total maximum reaction force were similar in reinforced concrete samples with the same diameter of reinforcement. These findings demonstrate SCC's total maximum reaction force, and for beams containing WP fibers with different volumetric percentages (0.5%, 0.75%, and 1%). The reasons explained above are also related to the role of WPFs in increasing the total reaction forces due to the qualities of sizable compressive strength and sufficient tensile strength, taking into account that both tensile and compressive strength are very important in concrete. The outcomes of testing impact loads showed that adding WPFs to concrete increases impact resistance, and this can be attributed to the ability of WPFs to absorb the energy resulting from impact loads, transforming concrete to a more ductile material. In addition, fibers reduce the crack width and crack bridging leading to large energy absorption concrete. The addition of WPFs with different volumetric ratios in SCCs has a positive effect as it raises impact resistance and thus raises the total maximum reaction force for all mixes concrete containing fibers. After the volumetric ratio of 0.75%, the total maximum reaction force began to decrease but it was still higher than that of the reference mix. The concrete exhibits ductile rather than brittle behavior as the outcome of the inclusion of WPFs.

3) Effect of Test Variables on the Impact Behaviors

Table VI portrays the impact responses with respect to the test variables. The values of total maximum reaction force, maximum deflection, and residual deflection are shown. Table VI confirms that the impact responses were affected by the experimental variables. The deflection and the remaining deflection values are inversely proportional to the PET ratio in the concrete mix and rebar diameters. After the result comparison, the following were noted:

- The first collection of SCCs beams reinforced with ($\rho_{\max}$) had variable WPFs percentages of (0, 0.5, 0.75, and 1%) under impact loading. The findings reveal that the use of WPFs has a positive impact on every beam in this group. Using such fibers had an improvement in SCC beam behavior. The deflection value at the stage of failure was reduced when compared to reference mix SCC beams. It can be established that when employing 1% WPFs, the amount of the maximum deflection during the first impact was 24.23% less than that of the beams made by the reference mix. The highest increase in the value of the total maximum reaction force according to the reference SCCs beam was 18% and was achieved when using 0.75% WPFs. The significant effects of combining longitudinal steel reinforcement and WPFs become more apparent in this group when compared to the other groups.

  The second collection of SCCs beams was reinforced with $\rho_{max} > \rho > \rho_{min}$. The observations that can be inferred are the same as those reached above. The greatest reduction in the value of maximum deflection during the first impact, compared to the reference SCCs beam, was equal to 35.9%. This reduction was achieved by incorporating WPFs with a volumetric ratio of 1%. The maximum increment in the value of total maximum reaction force according to the reference RC beam was 21.77%. This was achieved when employing WPFs with a volumetric ratio equal to 0.75%.

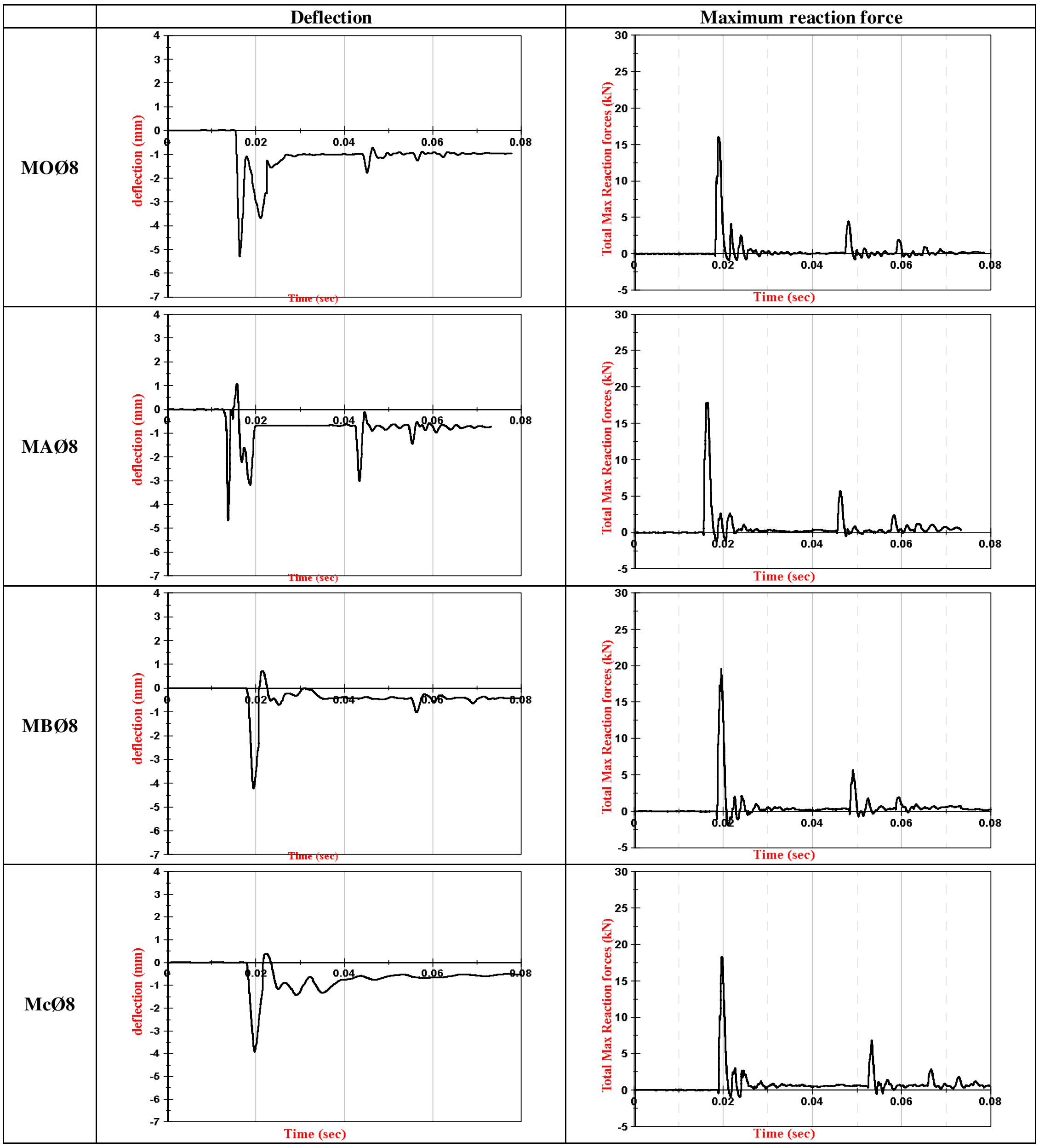

Fig. 6. Deflection time history and total maximum reaction force for the first group ($\rho_{max} > \rho > \rho_{min}$).

TABLE VI. IMPACT RESPONSES OF TOTAL MAXIMUM REACTION FORCE, MAXIMUM DEFLECTION, AND RESIDUAL DEFLECTION

Group	Beam	WPF %	Total Maximum reaction force (KN)	Increment (%)	Maximum deflection (mm)	Decrease (%)	Residual deflection (mm)
G1 Ø10 (ρ_{max})	MOØ10	0%	23.5	0	3.317	0	0.25
	MAØ10	0.5%	25.28	7.57	3.04	8.97	0.198
	MBØ10	0.75%	27.73	18	2.837	16.9	0.062
	MCØ10	1%	26.67	13.49	2.67	24.23	0.091
G2 Ø8 (ρ)	MOØ8	0%	16.03	0	5.3	0	0.82
	MAØ8	0.5%	17.84	11.29	4.67	13.5	0.77
	MBØ8	0.75%	19.52	21.77	4.21	25.89	0.49
	MCØ8	1%	18.29	14.09	3.9	35.9	0.65
G3 Ø6 (ρ_{min})	MOØ6	0%	13.7	0	6.89	0	3.09
	MAØ6	0.5%	16.2	18.24	5.68	21.3	2.99
	MBØ6	0.75%	17.889	30.57	5.14	34.05	2.9
	MCØ6	1%	16.67	21.67	4.71	46.28	2.97

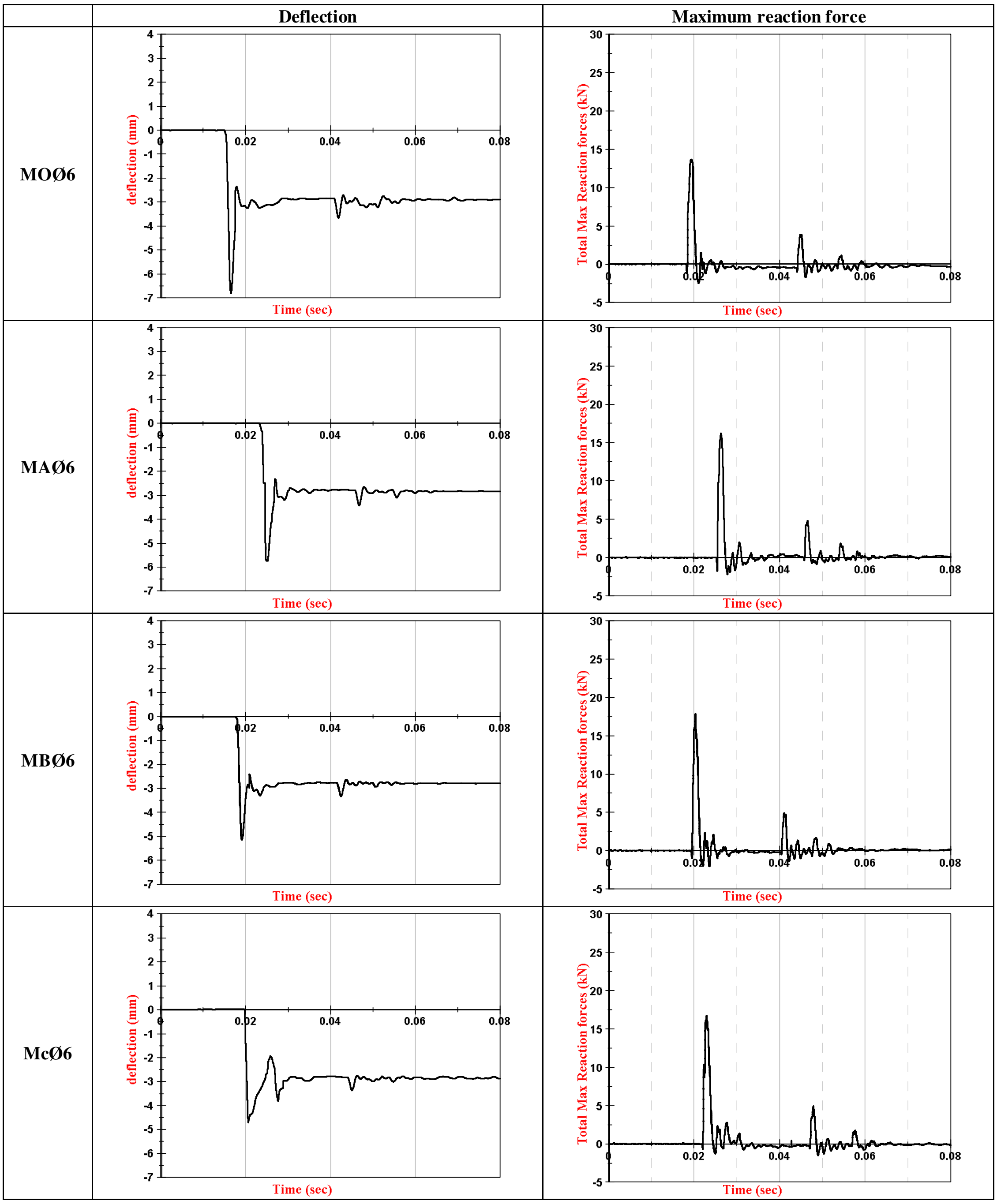

Fig. 7. Deflection time history and total maximum reaction force for first group (ρ_{min}).

- The third group of SCCs beams was reinforced with the minimum area of steel (ρ_{min}). The combined effect of longitudinal steel reinforcement and WPFs in this group appears to be lower than in the other groups, due to the minimum amount of steel utilized for the reinforcement of the SCCs beams in this group. However, the addition of WPFs had a significant influence on reducing the maximum deflection. The highest reduction achieved in the value of maximum deflection during the first impact was equivalent to 46.28% compared to the beam made with the reference mix. This reduction was achieved when using WPFs with a volumetric value of 1%. The maximum increment in the value of total maximum reaction force in comparison with the reference SCCs beam was 30.57%, achieved when using WPFs with a volumetric ratio equal to 0.75%.
- It can be concluded that, when the reinforcement ratio is held constant, increasing the proportion of plastic fibers has a noticeable impact on the maximum deflection and residual deflection values, reducing both. This indicates that

the addition of fibers augmented the ductility of concrete beams made of SCC and containing WPFs.

- When waste plastic fibers and steel reinforcement were combined in reinforced concrete beams subjected to impact loading, their synergistic effect can lead to improved performance. Generally, they are able to bridge the cracks and redistribute the stresses in the beam body to carry more load with a smaller deflection at the same load level [35].

IV. CONCLUSION

The current research study significantly advances the comprehension of the structural behavior of Self-Compacting Concrete (SCC) beams after the inclusion of plastic fibers, with a specific focus on deflection and reaction characteristics. In practice, plastic waste fibers can be added to reduce the deflection and reaction of SCC beams, especially when there is a pressing need to eliminate the deflection without increasing beam's depth. Based on the findings of the experimental investigation, the following conclusions can be derived:

Adding 0.75% plastic waste fibers to concrete mixtures has a number of benefits, including increased compressive strength up to 11.065%, increased modulus of elasticity up to 4.984%, increased splitting strength up to 22.929% and increased maximum reaction force. Beyond this addition percentage, compressive strength, modulus of elasticity, splitting strength, and maximum reaction force are decreased. Furthermore, maximum deflection and residual deflection are decreased, and the significant effects of combining longitudinal steel reinforcement and plastic waste fibers become more apparent in the first group (ρ_{max}). When increasing the reinforcement ratio, better performance was seen under impact loading circumstances. As the reinforcement ratio increased, there was a discernible decrease in the SCFRC beams' maximum and residual deflections during the initial impact event. Additionally, the behavior was better when the reinforcement ratio was larger, especially when it came to deflection recovery.

Overall, the incorporation of plastic waste fibers in a concrete mixture can enhance its mechanical properties, increase its cracking resistance, and improve the distribution of forces within the material. The specific benefits and performance improvements depend on the ratio of plastic waste fibers. The optimum ratio of 0.75% is recommended.

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