Structural Engineering and Mechanics, *Vol. 62, No. 3 (2017) 373-380*
DOI: https://doi.org/10.12989/sem.2017.62.3.373

Impact resistance of polypropylene fiber reinforced concrete two-way slabs

Rajai Z. Al-Rousan*, Mohammed A. Alhassan and Harith Al-Salman

Department of Civil Engineering, Jordan University of Science and Technology, Irbid, Jordan

(Received August 24, 2016, Revised February 10, 2017, Accepted February 24, 2017)

Abstract. Concrete structures are often subjected to long-term static and short-term dynamic loads. Due to a relatively low tensile strength and energy dissipating characteristics, the impact resistance of concrete is considered poor. This study investigates the feasibility of using polypropylene fibers to improve the impact resistance of reinforced concrete slabs. Fourteen polypropylene fiber reinforced concrete slabs were fabricated and tested using a drop weight test. The effects of slab thickness, fiber volume fractions, and impact energy on the dynamic behaviors were evaluated mainly in terms of impact resistant, crack patterns, and failure modes. The post impact induced strains versus time responses were obtained for all slabs. The results showed that adding the polypropylene fiber at a dosage of 0.90% by volume of concrete leads to significant improvement in the overall structural behavior of the slabs and their resistance to impact loading. Interestingly, the enhancement in the behavior of the slabs using a higher fiber dosage of 1.2% was not as good as achieved with 0.90%.

Keywords: impact resistance; polypropylene fibers; fiber-reinforced concrete; slabs; drop weight test; crack patterns

1. Introduction

Concrete is one of the most widely used building materials. It has many advantages over other building materials, such as flexibility in formation and service re-resistance, durability, ease of production, and economy. However, there are shortcomings such as its heavy weight, low tensile strength and brittle behavior; tensile strength of concrete is nearly one tenth of its compressive strength (Parveen and Ankit 2013). As a result, concrete is unable to withstand tensile loads and impact loads which are usually faced in structural elements, and therefore it is reinforced with steel to compensate for the lack of ductility and tensile strength.

Fibers addition to concrete reduces the occurrence of cracks, increases the tensile strength of concrete and gives it some flexibility. Fibers are mostly discontinuous and randomly distributed throughout the cement matrices leading to enhanced performance in terms of crack control system, toughness, impact resistance, ductility (post cracking), and tensile strength. Types of fibers that are typically used in concrete include polypropylene fibers, glass fibers, and steel fibers (Ghanem 2009, Campione 2011, Orod *et al*. 2016, Omer *et al*. 2015, Rabin *et al*. 2014, Mohamed *et al*. 2012).

1.1 Polypropylene fibers

Polypropylene fibers are gaining reputation due to their affordability and their high alkaline resistance. They are available in two forms, i.e., monofilament or fibrillated, manufactured in a continuous process by extrusion of a polypropylene homo-polymer resin (Keer 1984). Micro synthetic fibers based on 100% polypropylene are used extensively in ground-supported slabs for the purpose of reducing plastic shrinkage cracking and plastic settlement cracking. These fibers are typically 12 mm long with 18 μm diameter (Perry 2003). Polypropylene fibers are added in the recommended dosage of about 0.90 kg/m^3 (0.1% by volume) (Keer 1984); mixing techniques require little or no regular exercise (Newman and Choo 2003). The fiber can be added either in the traditional mixing plant or by hand to the ready-mixed concrete truck at the site. Knowledge of fresh concrete properties is necessary for the proper design and application of fiber reinforced concrete admixtures. Polypropylene fibers work mechanically; giving a coherent effect through the water held in or near the surface of the concrete, and delay evaporation and retains water-increasing cement. The introduction of polypropylene fibers into the concrete mix has generally no significant effect on the 28-days compressive strength of concrete (Keer 1984). Similarly, it has either little or no effects on the flexural strength of concrete (Ramakrishnan 1987). However, the toughness/energy absorption of the material generally measured as the area under the load-deflection curve is increased, especially at higher fiber content. This can be attributed to the influence of fibers through providing internal confinement to the concrete and participating in the energy absorption and dissipation though breaking, especially after formation of cracking. On the other hand, the surface of abrasion resistance and the resistance to frost attacks are significantly enhanced by the addition of polypropylene fibers. Also, the protection of the steel reinforcement against corrosion and reduce the water permeability of the concrete can be indirectly achieved by using polypropylene fibers (Ramakrishnan 1987). As a result, polypropylene fibers are generally more durable than

∗Corresponding author, Ph.D.
E-mail: rzalrousan@just.edu.jo

http://www.techno-press.org/?journal=sem&subpage=8
ISSN: 1225-4568 (Print), 1598-6217 (Online)

plain concrete (Ma *et al*. 2004).

1.2 Impact loading

Impact loading is recognized as the load resulting from collision between two bodies during a very small interval of time. The impact load applied to a structure depends on the striker's velocity, the structure and the striker masses, the resulting deformations and the material properties of both bodies. Some common examples of impact loading in the field of civil engineering are vehicle collision with a structure, impact accidents during construction, ship's collision with offshore structures or gravity platforms, blows on concrete piles during driving, collision between the structure and a mass which is flying away accidentally from a rotating machinery inside the structure, rocks falling on roof of protection shelters, and aircraft collision with structure. In general, the effects of impact on structures can be classified into local impact response and global impact response. The local impact effects may be in the form of concrete spalling, scabbing, penetration or perforation of the target. Spalling of concrete is the ejection of pieces of concrete from the front face region surrounding the area of impact. Scabbing consists of the ejection of pieces of concrete from the back of the target opposite to the impact area, thus leaving a back crater after the impact. Penetration is the depth to which a projectile enters a massive concrete target without passing through it. Perforation occurs when the projectile just passes completely through the target (Elavenil and Samuel 2012). When a hard projectile moving at a high speed collides, impact energy is absorbed locally. Therefore, damage is concentrated in the vicinity of the impact region. Many empirical formulas were developed to predict the penetration depth and the minimum target thickness required to prevent scabbing and perforation. These formulas depend on the impact velocity, material properties of the projectile and the target, and mass and shape of the projectile. A potential flexural or shear failure will occur if the strain energy capacity of the concrete and supports is smaller than the part of kinetic energy transmitted from the zone of penetration or perforation into the concrete. The dynamic response of structures subjected to impact can be determined if the applied force-time history is known. In the design of concrete structures against impact loads, it is necessary to investigate both the local and overall impact responses. Therefore, a wide interest during the past decades by many researches (Sawan and Abdul-Rohman 1986, Banthia *et al*. 1987, Murtiadi 1999, May *et al*. 2006) focused on understanding the real behavior of the structures under dynamic loads such as impact, blast or earthquake loads.

Fiber-reinforced concrete (FRC) in civil engineering applications were fairly limited until about ten years ago, when significant attention was made to these materials for repair and retrofit of structures. Most of the research conducted on FRC applications concentrated on static and pseudo dynamic loadings. There are many situations in which structures undergo impact or dynamic loading, such as when there is an explosion, impact of ice load on pile structures, accidental falling loads, tornado-generated projectiles, etc. The characteristics of impact load are different from those of static and seismic loads. Since the duration of loading is very short, the strain rate of material becomes significantly higher than that under static and seismic loading. Also, structural deformation and failure modes will be different from those under static and seismic loading.

Due to a relatively low tensile strength and energy dissipating characteristics, the impact resistance of concrete is considered poor. In this study, the dynamic behavior and the absorbed energy of impact loads are investigated experimentally by testing Polypropylene Fiber Reinforced Concrete (PFRC) slabs. The parameters that were investigated include the polypropylene fiber volume fraction, the slab thickness, and impact energy. Fourteen PFRC slabs were fabricated and tested using a drop weight test.

2. Research significance

Current world events dictate the need for protecting essential structures from increased attacks or crashing accidents. Reinforced concrete slabs and floor systems are typically responsible for maintaining the integrality of the structure at each floor level. Their resistance to impact loading is of significant importance to the overall stability of the structure. Accordingly, the feasibility of utilizing discontinuous polypropylene fibers to improve the resistance of reinforced concrete slabs to impact loading is explored. This study is innovative in terms of the used fiber type and contents as well as the implemented drop-weight test setup and instrumentation for capturing the post impact response of the slabs within a very short period of time.

Table 1 Specimens' details and test results

Slab	Percent of fibers by volume	Slab thickness, m	Height of the falling mass, m	Max induced strain after impact, $\mu\varepsilon$	ER[1] (10^{-9}), second
Sf0.0t0.07h2.4	0			3088	267
Sf0.3t0.07h2.4	0.30%			1719	148
Sf0.6t0.07h2.4	0.60%	0.07		1547	134
Sf0.9t0.07h2.4	0.90%			987	85
Sf1.2t0.07h2.4	1.2%		2.40	1399	121
Sf0.0t0.09h2.4	0			2334	202
Sf0.3t0.09h2.4	0.30%			1289	111
Sf0.6t0.09h2.4	0.60%	0.09		1175	102
Sf0.9t0.09h2.4	0.9%			742	64
Sf1.2t0.09h2.4	1.20%			1017	88
Sf0.6t0.07h1.2	0.60%	0.07		1161	100
Sf0.9t0.07h1.2	0.90%		1.20	544	47
Sf0.0t0.09h1.2	0	0.09		1896	164
Sf0.9t0.09h1.2	0.90%			424	37

[1]ER: Energy released defined as the area under the concrete strain versus time curve

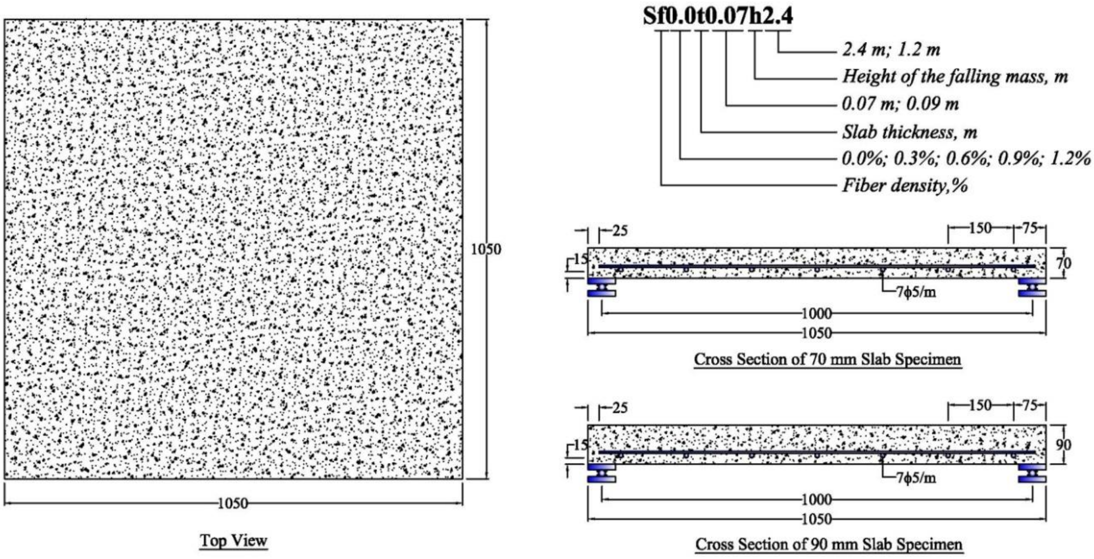

Fig. 1 Tested slabs layout and details (all dimensions in mm)

Table 2 Mixture ingredients and proportions

Ingredient	kg/m^3
Cement	375
Coarse Aggregate (CA	916
Fine Aggregates	700
Silica Sand	64
Plasticizer	1.5
W/C	0.40

3. Description of experimental program

3.1 Test specimens

The experimental program included testing fourteen simply supported, two-way reinforced concrete slabs with equal length and width of 1.05 m as shown in Fig. 1. The investigated parameters are listed in Table 1, which shows two slab thicknesses (t): 7 cm and 9 cm, five fiber volume fractions (f): 0%, 0.3%, 0.6%, 0.9%, and 1.2%, and two different drop weight heights (h): 1.2 m and 2.4 m. Seven steel bars with a diameter of 5 mm were used in each direction in all specimens, resulting in a steel reinforcement ratios of 0.0025 and 0.0018 for the 7 cm and 9 cm slabs, which meets the minimum ratio according to the ACI 318-14 Code (ACI318 2014). A dropped mass representing the dynamic load is performed using a steel ball (10 cm in diameter and weighs 7 kg) freely dropped on the center of the slab.

3.2 Concrete mixture

Table 2 shows the mixture ingredients and proportions per cubic meter. Local coarse and fine aggregates were used with specific gravities of 2.5 and 2.6, respectively. Type I ordinary cement was used in all of the batches with different volume fractions of polypropylene fibers. Polypropylene fibers with a monofilament configuration were used. According to the manufacturer, the used polypropylene fibers can decrease plastic and drying shrinkage cracking and increase impact resistance in young concrete. The fibers act mechanically to reinforce the concrete with multi-dimensional fiber network coated with mortar. The used polypropylene fibers have a length of 19 mm, specific gravity of 0.91, tensile strength of 165 MPa, and excellent alkali resistance. Once all the ingredients were consistently mixed, the fibers were introduced as the last step. In order to ensure a uniform distribution within the concrete, the polypropylene fibers were added manually in small quantities dispensed within the mixer while running. The mixing continued for sufficient time after introducing the fibers to ensure uniform distribution without any crumpling or balling of fibers. All specimens were de-molded 24 hours after casting and place in lime-saturated water to cure for 28 days.

3.3 Test setup and instrumentation

The main supporting frame is a three dimensional structure consists mainly of steel members with I-section, joined together so as to provide a horizontal platform to give simply supported condition for the slab specimens. The supporting columns are four steel members with I-section braced together in both directions to avoid skewing, which might cause eccentric loading. The vertical guide is composed of a perforated hollow tube member; 150 mm in diameter placed vertically to allow for applying the load on the top surface of the tested specimens as shown in Fig. 2. The vertical tube is supported and kept in position by means of a three dimensional frame of 1.075 m in height and 1.010 mm in width, fabricated using hollow steel square sections of 25 mm size. The striking object used is a steel ball of 7 kg mass with adjustable heights of 1.2 m to 2.4 m. The steel ball is allowed to fall freely, thus, striking the top surface of the tested specimens at the center. Uniaxial electrical resistance strain gauges (25 mm long) were used to measure the strain in concrete slabs. Four strain gauges were used in

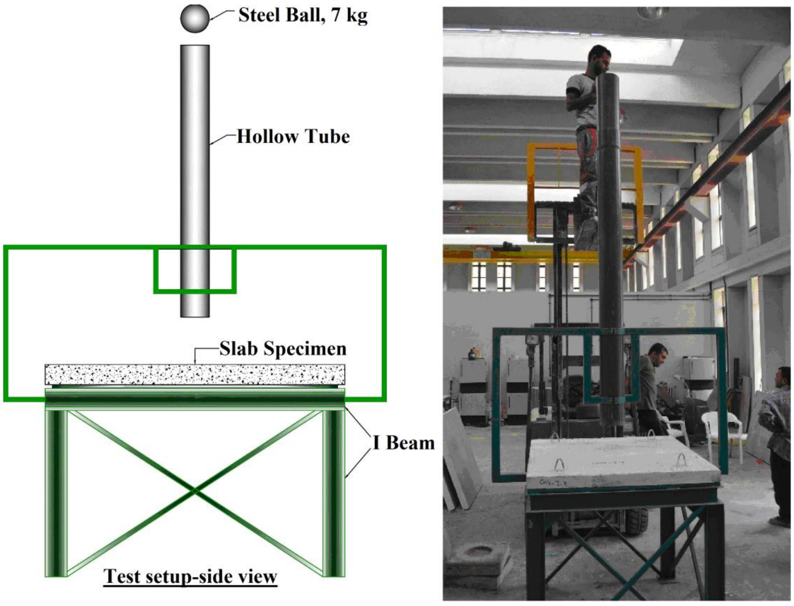

Fig 2 Test setup

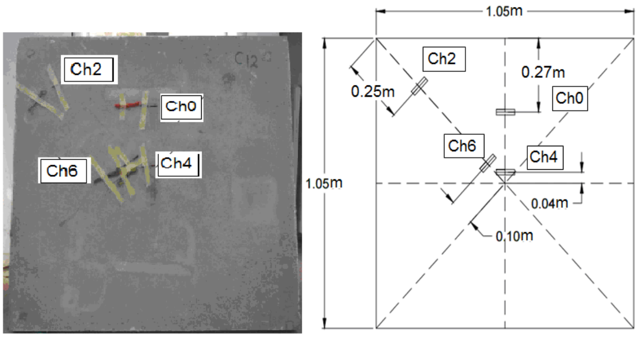

Fig. 3 Locations of the strain gauges

Table 3 Compressive and splitting tensile strengths and dynamic modulus

Fiber volume fraction, %	Average compressive strength, MPa	Average splitting tensile strength, MPa	Maximum strain, $\mu\varepsilon$	Modulus of elasticity (MPa)
0	38.9 (0.0%)	2.92 (0.0%)	3960 (0.0%)	16,626 (0.0%)
0.3	40.8 (4.7%)	3.13 (7.2%)	3850 (-2.9%)	17,934 (7.9%)
0.6	42.4 (8.9%)	3.34 (14.4%)	3770 (-4.9%)	19,024 (14.4%)
0.9	44.3 (13.8%)	3.42 (17.1%)	3660 (-7.6%)	20,481 (23.2%)
1.2	42.1 (8.1%)	3.27 (12.0%)	3290 (-16.8%)	21,617 (30.0%)

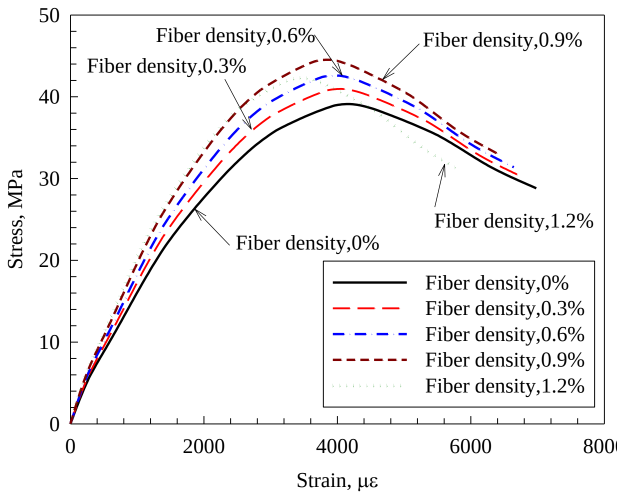

Fig. 4 Stress-strain diagrams of concrete cylinders

each slab at four selected locations as illustrated in Fig. 3. For the strain measurements, a special data logger was used that allows for simultaneous sampling and higher-speed acquisitions, which is necessary to capture the results at the four different locations within a very short period of time after the impact.

4. Experimental results and discussion

4.1 Concrete strength results

Table 3 shows the compressive and splitting tensile strengths of the tested cylinders. Inspection of Table 3 reveals that the maximum compressive and splitting tensile strengths were obtained from the specimens containing 0.90% of polypropylene fiber with an increase of 13.8% and 17.1%, respectively, with respect to the control ones without polypropylene fiber. In addition, it can be observed that the compressive and tensile strengths increased with the increasing of polypropylene content till 0.90% and then decreased for the 1.2% content. This could be attributed to the fact that at fiber volume fraction of 1.2%, the workability of the concrete became very small, and additional water was needed to mix and finish the concrete, resulting in a reduction in the strength properties. The results also show that the polypropylene fibers had higher effect on the tensile strength than the compressive strength.

The stress-strain diagrams for the concrete batches with different fiber volume fractions are shown in Fig. 4. After an initial linear portion up to about 30-40% of the ultimate, the curves become non-linear and the non-linearity is

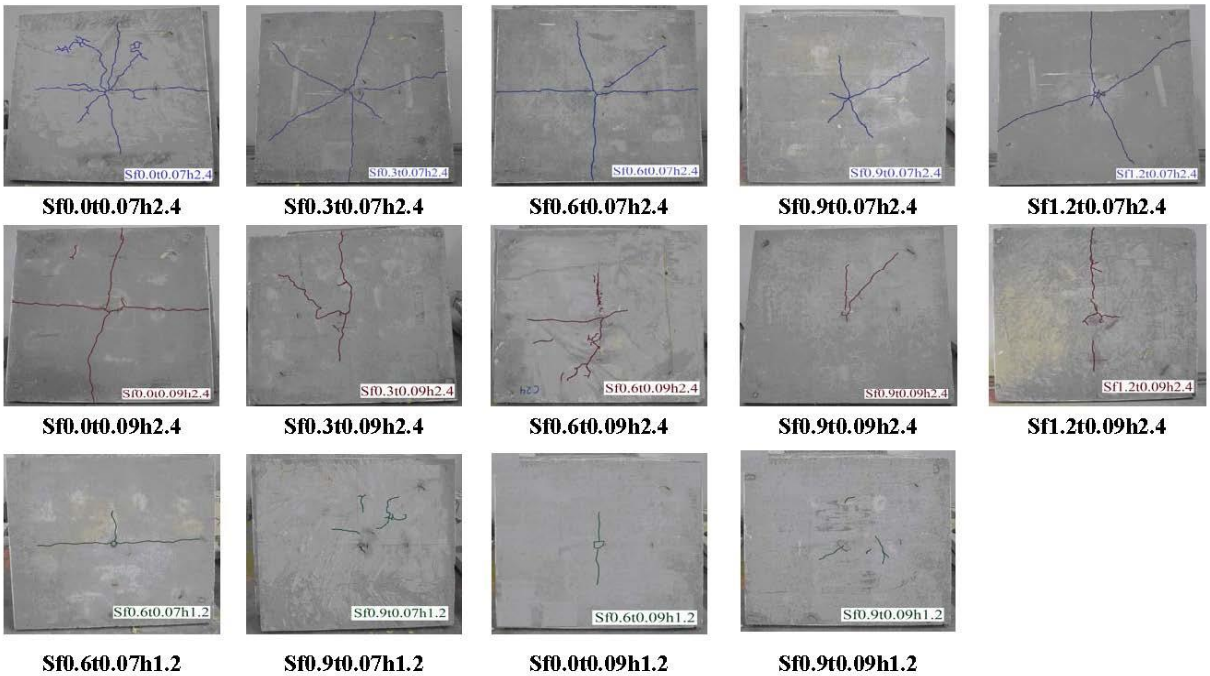

Fig. 5 Crack patterns in the tested slabs

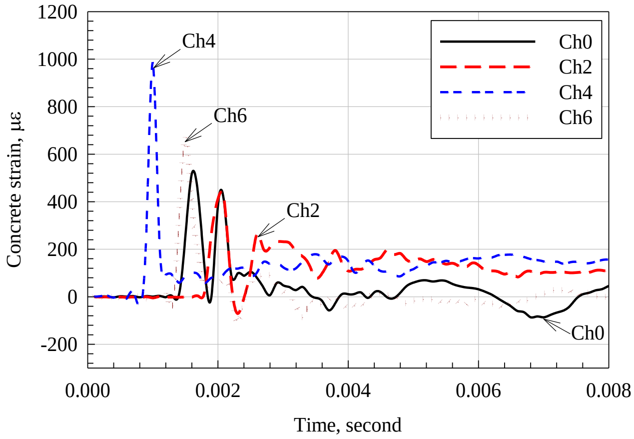

Fig. 6 Typical induced strains versus time after impact for Sf0.9t0.07h2.4

primarily a function of the coalescence of micro cracks at the paste-aggregate interface. The ultimate stress is reached when a large crack network is formed within the concrete, consisting of the coalesced micro cracks and the cracks in the cement paste matrix. The dynamic moduli of elasticity listed in Table 3 are calculated from the slope of the linear portion of the stress-strain diagram. As the slope of the diagram increases, the dynamic modules of elasticity increases and the resistance to impact load increases. The increase in the dynamic modulus of elasticity relative to the concrete batch without fibers is 7.9%, 14.4%, 23.2% and 30.0% for the concrete batches with fiber volume fractions of 0.3%, 0.6%, 0.9 and 1.2%, respectively. Also, the concrete strain corresponding to ultimate stress is ranging from 0.00396 for concrete with 0% fiber to 0.00329 for concrete with 1.2% fiber with a reduction percentage of 16.8%.

4.2 Crack patterns

Control reinforced concrete slabs (Sf0.0t0.07h2.4 and Sf0.0t0.09h2.4); i.e., slabs without polypropylene fibers, showed a large range of cracks distributed over the entire specimen and passing through four out of three strain gauges connected to the specimen. This indicates that the control slabs were highly affected by the impact load as shown in Fig. 5. Inspection of Fig. 5 reveals that the increasing polypropylene fiber content up to 0.9% (Sf0.9t0.07h2.4) had a strong influence on the crack patterns by reducing the number and distribution of cracks. This is an indication to the effectiveness of the added fibers in improving the cracking resistance of the concrete and reducing the cracks propagation. The fibers intercept the cracks and for propagation, rupture of fibers is required.

As the fibers content increased up to 0.9%, more fibers intercepted the cracks resulting in a better cracking patterns. The number of cracks and distribution slightly increased for fiber content of 1.2% (Sf1.2t0.07h2.4). Also, for the two slab thicknesses (Sf0.0t0.07h2.4 and Sf0.0t0.09h2.4), the effect of fiber content on the crack patterns and distribution was similar as shown in Fig. 5. As expected, the crack distribution and numbers decrease with the decrease of the impact energy from the height of 2.4 m (Sf0.6t0.07h2.4) to 1.2 m (Sf0.6t0.07h1.2) as shown in Fig. 5.

4.3 Strain-time response

Fig. 6 shows a typical induced strain versus time for slab Sf0.9t0.07h2.4. As shown in Fig. 6, the maximum strain reading is obtained at Ch4 (located at 4 cm from the center of the slab), followed by Ch 6 (located at 10 cm from the center of the slab), then Ch0 (located at 23.3 cm from the center of the slab), and finally the minimum strain

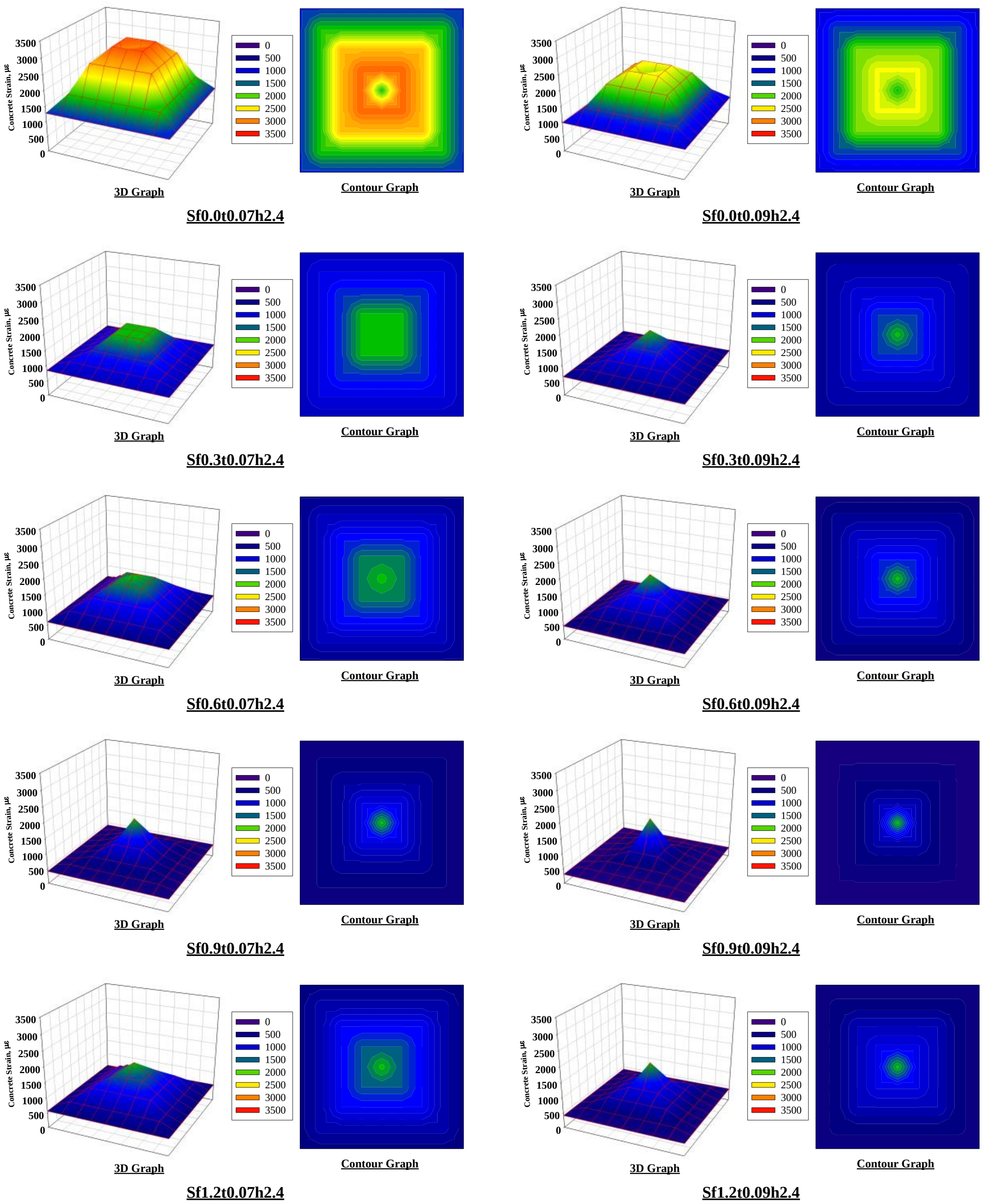

Fig. 7 Concrete strain contours and 3D strain graphs for 2.4 m drop weight height

reading is obtained at Ch 2 (located at 46 cm from the center of the slab). Therefore, the concrete strain decreased with the increase in the distance from the center of the slab. The maximum strain reading of 9870 με at a time of 0.001 second for Ch4 followed by Ch 6 with a strain of 6738 με at a time of 0.00151 second then Ch0 with a strain of 5189 με at a time of 0.00163 second and finally the minimum strain reading of 4105 με at a time of 0.00207 second for Ch2.

Figs. 7 and 8 show the concrete strain contours and 3D strain graphs for the 2.4 m and 1.2 m drop weight heights, respectively. Fig. 7 indicates that at a drop weight height of 2.4 m, the induced strains at all channels for the 9 cm thick slabs are lower than the companion 7 cm, with an average reduction percentage of 27%. As shown in Fig. 8, similar trend is also observed for the 1.2 m drop weight height, with an average reduction percentage of 33%

4.4 Comparisons

Table 1 shows the maxim strains obtained and

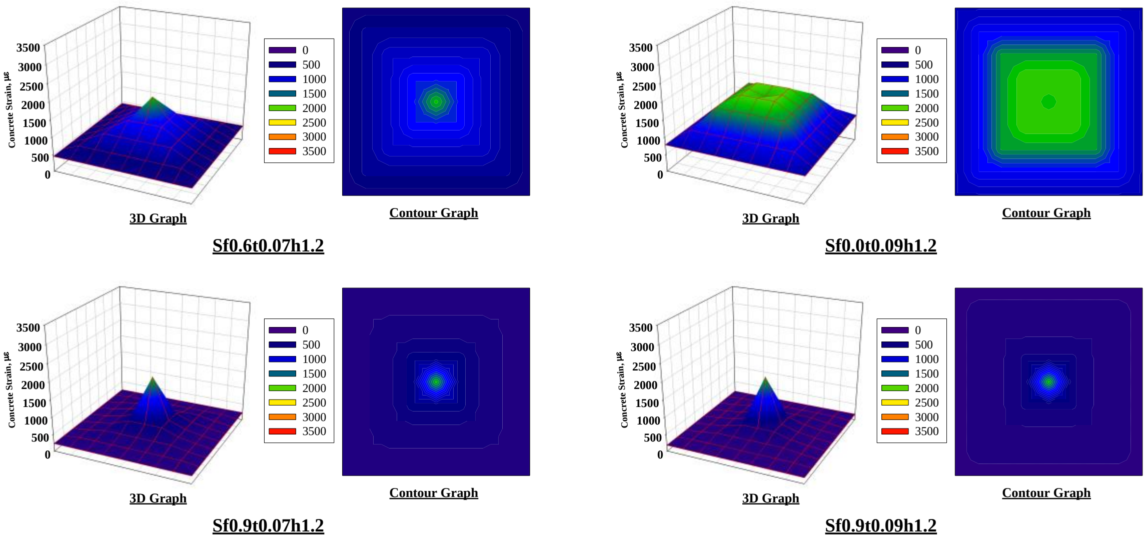

Fig. 8 Concrete strain contours and 3D strain graphs for 1.2 m drop weight height

corresponding energy released after impact for the various slabs. At a drop weight height of 2.4 m, the maximum strains for the 7 cm thick slabs were 3088, 1719, 1547, 987, and 1399 με for fiber contents of 0.0, 0.3, 0.6, 0.9, and 1.2%, respectively, with a reduction of 44%, 50%, 68%, and 55% with respect to the control slab without fibers. Also, Table 1 shows that the maximum strains for the 9 cm thick slabs were 2334, 1289, 1175, 742, and 1017 με for fiber contents of 0.0, 0.3, 0.6, 0.9, and 1.2%, respectively, with a reduction of 45%, 51%, 67%, and 56% with respect to the control slab without fibers. Therefore, the 0.9% was the optimum fiber volume fraction in term of concrete compressive and tensile strengths, crack patterns, and induced strains. Regarding the effect of the slab thickness, Table 1 indicates that the induced strains in the 9 cm thick slabs were 76, 75, 76, 75, and 73% of the induced strains in the companion 7 cm thick slabs for fiber contents of 0.0, 0.3, 0.6, 0.9, and 1.2%, respectively. Therefore, the thickness of slab has a major influence on its impact resistance in terms of the induced strains and crack patterns.

The maximum induced strains for the 7 cm slabs at a 1.2 m drop weight height were 1161 and 544 με for fiber contents of 0.6 and 0.9%, respectively, with a reduction of 25% and 45% compared with the companion slabs at a 2.4 m drop weight height as shown in Table 1. For the 7 cm slabs at a 1.2 m drop weight height, the maximum induced strains were 1896 and 424 με for fiber contents of 0.6 and 0.9%, respectively, with a reduction of 19% and 43% compared with the companion slabs at a 2.4 m drop weight height. As anticipated, increasing the height of the falling weight increased the magnitude of the induced strain, in addition to the increased number of cracks.

The energy released (ER) defined as the area under the concrete strain versus time curve, decreased with the increase of the fiber content as shown in Table 1. This reflects the efficiency of the fibers in resisting the impact load. The slab thickness also had a significant influence on reducing the ER, but to a lower degree than the fiber ontent. Similar trends were obtained at both drop weight heights.

5. Conclusions

Based on the results and observations, the following conclusions are drawn:

- Polypropylene fibers noticeably increase the compressive and tensile strengths of concrete and elastic modulus. They also reduce the impact-induced strains in concrete slabs, thus providing an enhanced resistant to impact loading.
- The optimum volume fraction of polypropylene fibers for improved performance and impact resistance of slabs is 0.90%.
- The performance enhancements using 1.2% fiber volume fraction were lower than the enhancements at 0.90%. This is attributed to problems in the workability of concrete at fiber volume fraction greater than 0.9%, thus leading to adverse effects on the strength properties and impact resistant.
- Strain-time histories of the two drop weight heights; i.e., 2.4 m and 1.2 m, for the 7 cm and 9 cm thick slabs, showed that polypropylene fibers do improve the impact resistance of concrete slabs.
- The influence of polypropylene fibers on the impact behavior was more pronounced in the 9 cm thick slabs compared with the companion 7 cm thick slabs in terms of the induced strains and crack patterns. Less number of cracks and better distributions occurred in the slabs containing 0.9% polypropylene fibers.

Acknowledgements

The work presented in this article was funded by the Deanship of Research at Jordan University of Science and Technology.

References

ACI Committee 318 (2014), "Building Code Requirements for Reinforced Concrete", (ACI 318-14) and Commentary (318R-14), American Concrete Institute, Farmington Hills, M.I.

Banthia, N.P., Mindess, S. and Bentur, A. (1987), "Impact behavior of concrete beams", *Mater. Struct.*, **20**(118), 293-302.

Campione, G. (2011), "Compressive behavior of short fibrous reinforced concrete members with square cross-section", *Struct. Eng. Mech.*, **37**(6), 649-669.

Elavenil, S. and Samuel Knight, G.M. (2012), "Impact response of plates under drop weight impact testing", *Daffodil Int. Univ. J. Sci. Tech*., **7**(1), 1-11.

Ghanem, A. (2009), "Behavior of reinforced concrete slabs under impact", PhD Thesis, Department of Civil Engineering, College of Engineering, University of Baghdad.

Ibraheema, O.F., Abu, B. and Joharib, I. (2015), "Behavior and crack development of fiber-reinforced concrete spandrel beams under combined loading: an experimental study", *Struct. Eng. Mech.*, **54**(1), 1-17.

Keer, J.G. (1984), "New reinforced concretes: concrete technology and design", Ed. Swamy, R.N., Surrey University Press, **2**(1), 2-105.

Ma, Y., Zhu, B., Tan, M. and Wu, K. (2004), "Effect of type polypropylene fiber on plastic shrinkage cracking of cement mortar", *Mater. Construct.*, **37**(1), 92-95.

May, I.M., Chen, Y., Owen, D.R.J., Feng, Y.T. and Thiele, P.J. (2006), "Reinforced concrete beams under drop-weight impact loads", *Comput. Concrete*, **3**(2-3), 79-90.

Murtiadi, S. (1999), "Behavior of high-strength concrete plates under impact loading", M.Sc. Thesis, Faculty of Engineering and Applied Science, Memorial University of Newfoundland.

Newman, J. and Choo, B. (2003), *Advanced Concrete Technology 3: Processes*, 1st Edition, Elsevier Ltd, Oxford.

Parveen, I. and Ankit, S. (2013), "Structural behavior of fibrous concrete using polypropylene", *Int. J. Eng. Res.*, **3**(3), 1279-1282.

Perry, B. (2003), "Reinforcing external pavements with both large and small synthetic fibers", *High Beam Res.*, **37**(8), 46-47.

Ramakrishnan, V. (1987), "Materials and properties of fibre reinforced concrete", *Proc. of ISFRC*, **1**(1), 3-24.

Safan, M.A. (2012), "Behaviour of fiber reinforced concrete beams with spliced tension steel reinforcement", *Struct. Eng. Mech.*, **43**(5), 623-636.

Sawan, J. and Abdul-Rohman, M. (1986), "Impact effect on RC slabs: experimental approach", *ASCE J. Struct. Eng.*; **112**(9), 2057-2065.

Tuladhar, R. and Lancini, B.J. (2014), "Ductility of concrete slabs reinforced with low-ductility welded wire fabric and steel fibers", *Struct. Eng. Mech.*, **49**(4), 449-461.

Zarrin, O. and Khoshnoud, H.R. (2016), "Experimental investigation on self-compacting concrete reinforced with steel fibers", *Struct. Eng. Mech.*, **59**(1), 133-151.

CC