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Effect of internal short fibers, steel reinforcement, and surface layer on impact and penetration resistance of concrete

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Abstract This paper presents an experimental program to investigate the impact and penetration resistance of concrete. The research work is divided into two approaches. These approaches are effect of concrete constituents and effect of surface layer. Effect of concrete aggregate type, w/c ratio, fiber type, fiber shape, fiber volume fraction, and steel reinforcement is considered in the first approach. The second approach includes using fiber reinforced concrete and glass fiber reinforced polymer as surface layers. The evaluating tests include standard impact test according to ASTM D 1557 and suggested simulated penetration test to measure the impact and penetration resistance of concrete. The test results of plain and fibrous concrete from ASTM D 1557 method indicated that steel fiber with different configurations and using basalt have a great positive effect on impact resistance of concrete. Moreover, the simulated penetration test indicates that steel fibers are more effective than propylene fibers, type of coarse aggregate has negligible effect, and steel fiber volume fraction has a more significant influence than fiber shape for reinforced concrete test panels. Finally, as expectable, surface properties of tested concrete panels have a significant effect on impact and penetration resistance.

1. Introduction

Penetration and impact events happen in a wide variety conditions; they may occur as an unplanned process such as randomly dropped objects and the collision accidents in all forms as cars, trains, and aircrafts as well as effect of the natural phenomena in some situations [1]. In addition, they can be part of a driven action as using the equipments in the construction industry such as driving piles and striking a nail with a

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hammer or because of military operations. Also, in the recent decades, the development of precision guided penetrating weapons provides a significant threat to military concrete facilities [2]. Therefore, improvement of concrete and reinforcement is strongly demanded to provide the structural elements an acceptable level of protection against penetration and impact loads. Some special structures and infrastructures such as dams, tanks, nuclear power stations, and the military defensive constructions as the shelters and different types of fortifications may face these types of accidental loads during their life.

The response and behavior of concrete subjected to dynamic loads and high loading rates explored extensively for both civil and military applications, understanding that response is essential to protect fortifications and shelters. For instance, the nuclear power plants and other structures of military facilities must survive the penetration and impact loading of an aircraft crash, penetrator, and missiles impact or non-contact air explosion [3,4].

Consequently, studying the behavior of concrete that is subjected to penetration and impact loads or blast is necessary. Experimentally, the response of concrete under impact loading is very difficult to capture. Moreover, several failure modes have been observed by many researches [5,6].

The impacting projectiles can be categorized as soft or hard depending on the relation between the concrete element stiffness and the projectile stiffness [7]. The missile impact or an explosion on a concrete area can lead to local damage including perforation, scabbing, scaling, and punching shear [8,9].

Improvements in penetrators by increasing penetrating power and range are accomplished by adjusting the length to the diameter ratio of the penetrator, the use of new materials such as tungsten and depleted uranium, the use of new propellants, new sabots and new stabilizing fin structures and materials. All of these changes require improvements in armors, and targets are constantly being improved in toughness, hardness, and obliquity and are being constructed in multilayer. Hence, the effect of the impacting missile can be briefly classified into local damage or global damage depending on the behavior of concrete that is subjected to the penetration and variety of other factors such as mass, material properties of missile, and its geometry [2].

Protecting concrete structures against impact includes two different approaches or techniques. One approach is to improve the concrete properties by increasing its strength or applying additional internal reinforcement (steel bars – fiber reinforcement) [10]. Another approach is to reduce damage by covering and protecting the concrete with external elements. These elements can act as a sacrificial layer able to absorb most of the kinetic energy of the projectiles. Moreover, in the case of samples (targets) protected or covered by fabric, they can effectively catch the debris and hold the scabbed crater from the back face of the targets [7].

The concrete mixture ingredients have a very important effect on enhancing the performance of the impacted concrete and make it more suitable for the different types of the impact and penetration loads [11,12]. The effect of coarse aggregate, fine aggregate, chemical admixtures, concrete compressive strength, and concrete tensile strength is presented in the following sections.

It is important to know that the energy during impact loading is consumed in the process of crack initiation and propagation in concrete. It is well known that microcracks are initiated at relatively low stress levels prior to fracture of concrete. As the stress is increased, these microcracks propagate and link up into larger cracks, which eventually form the fracture zone. A fracture zone in the interface of aggregate and the cement paste (i.e., the translation zone) characterizes the fracture of concrete. Coarse aggregates arrest crack growth, which produces meandering and branching of cracks [13,14]. Thus, the aggregate strength has a larger influence on the concrete strength which affects directly the impact and penetration resistance of the concrete targets. Hence, the impact resistance of concrete mainly depends on the properties of transition zone between aggregate and matrix [11]. The importance of coarse aggregate type on quality of transition zone can be illustrated by studying the shape of hysteresis loop during testing of the elastic modulus of concrete. Based on the loading–unloading curve of concrete obtained before the peak load, a wide hysteresis loop is an indication of a weak interface between the aggregate and matrix. From the experimental test results, lime stone-aggregate concrete has the narrowest hysteresis loop [15]. The maximum aggregate size also needs to be limited. There are two reasons which explain the negative effect of using large nominal maximum size of aggregate. Firstly, larger aggregates result in weaker interface between aggregate and cement paste due to the presence of water that usually occurs beneath coarse aggregates (bleeding). Secondly, small aggregate size decreases the probability of the presence of microcracks [10]. This is due to statistics stating that there is higher probability of a larger number of weakness zones existing in specimens of larger volumes. In addition, reduced aggregate size makes it more difficult for cracks to propagate in the cement paste, due to the reduced mean space between the aggregates at a constant aggregate content. Furthermore, surprisingly, small variations in aggregate content and grading result in large variations in workability of the fresh concrete [11]. For the impact and penetration resistance, Dancygier et al. [6] conclude that the larger the aggregate size and the harder the aggregates material (i.e., basalt and flint), the higher the perforation resistance (e.g., see the 12 mm and 50 mm flint aggregate and of the 22 mm and 50 mm basalt aggregates). This result can be associated with the presence of aggregate which are the hardest material in the concrete mix and provide much of the resistance to the penetrating projectile. This observation indicates that some of the energy was dissipated also by inflicting these scratches, and it supports the conclusion that harder coarse aggregate provides higher impact and penetration resistance [6].

As the coarse aggregate, the amount of sand in the concrete mix also plays an important role because the sand content largely determines the necessary amount of water that may indirectly determine the concrete compressive strength and also affects most of the mechanical properties of the hardened concrete which obviously influences the concrete resistance against the impact and penetration loads [11].

Studies on the development of hydration and mortar phase of concrete show that the increase in strength can be attributed to the improvement of paste–fine aggregate transition zone [10]. In addition, the fine aggregate increases the flowing ability and segregation resistance when used at a suitable amount. Also, the fine aggregate modifies the compressive strength of concrete when used in varying proportion with cement and coarse aggregate. It also affects on the impact and the penetration resistance of the concrete targets.

Several impact and penetration tests have been used to study the effect of steel reinforcement on the impact and penetration resistance of concrete. Most results showed that the amount of the reinforcement had a relatively large effect on the impact and penetration resistance of concrete targets, and penetration reduction of about 25% was observed for reinforced targets compared to those that were unreinforced. This reduction was obtained with extreme amount of reinforcement. In some penetration tests, the reinforcement volume fraction varied between 6.5% and 25%. Reinforcement amount of 1.55% by volume resulted in a penetration reduction of about 10% in comparison with unreinforced targets [2,10,11,16].

The presence of steel fibers in concrete mixtures may also have a significant effect on impact resistance of concrete. The role of randomly distributes discontinuous fibers is to bridge across the cracks that develops and provides some post-cracking "ductility." If the fibers are sufficiently strong, sufficiently bonded to material, permit the fiber reinforced concrete to carry more significant stresses over a relatively large strain capacity in the post-cracking stage [17]. The real contribution of the fibers is to increase the toughness and ductility of the concrete (defined as some function of the area under the load vs. deflection curve), under any type of loading. That is, the fibers tend to increase the strain at peak load and provide a great deal of energy absorption in post-peak portion of the load vs. deflection curve [6,18]. Therefore, the use of fibers in the concrete structure elements is to enhance their ductility and opens new ways to improve the performance of the concrete structures that may be subjected to impact or penetration loadings. The experimental test results showed that the smallest penetration depth was caused in the concrete specimens with the steel fibers reinforcement [10]. Limited studies were employed to reinforce the concrete by covering the concrete elements that were exposed to the impact or penetration loading [18].

2. Materials and experimental program

2.1. Materials

Ordinary Portland cement (ASTM Type I) was used throughout the program. The chemical analysis and mechanical and physical properties of this cement are presented in Table 1. This cement type is classified in Egyptian standard ES 47561/2006 as CEM I 32.5N. Natural siliceous sand with 2.51 fineness modulus was used. Pink limestone and crushed basalt with 12.5 mm maximum aggregate size were used as coarse aggregate. The hardness of coarse aggregate using Los Angeles test according to ASTM C 535 for pink limestone and crushed basalt are 20.0% and 14.5%, respectively. The grading of sand and coarse aggregate are presented in Table 2. High range water reducing admixture Type F was used. The dose of chemical admixture was experimentally determined by trials to achieve 90 ± 10 mm slump.

Two types of fibers were used in this study: the first one was polypropylene fibers and the second was steel fibers with three different subtypes with different shapes. The polypropylene fibers used in this research have a length (18 ± 1) mm approximately, equivalent diameter 0.15 mm, 120 aspect ratio, and specific gravity 0.9. The steel fibers were straight, hooked, and waved as shown in Fig. 1. Description of each type of steel fibers is presented in Table 3.

Two directions glass fibers reinforced polymer (GFRP) woven was used as sacrificial cover layer in some specimens. Some of its specifications are tabulated in Table 4. Plain steel bars of 8 mm diameter were used with different spacing and configuration types. The yield strength, ultimate strength, and percentage of elongation of steel reinforcement bars are 352 MPa, 510 MPa, and 22%, respectively.

2.2. Experimental program

2.2.1. Studied parameters

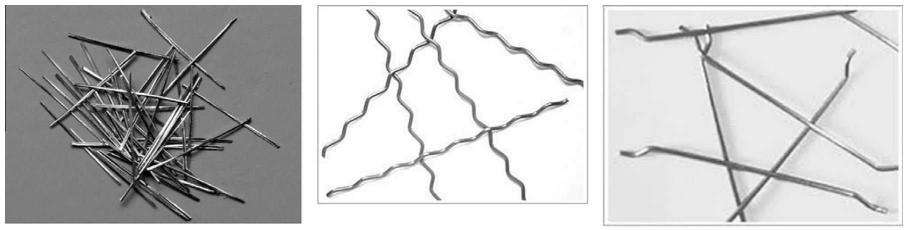
This research work divided into three sections. These sections include impact and penetration resistance of concrete without internal steel bars (plain concrete and fibrous concrete), impact and penetration resistance of concrete reinforced with steel bars (with and without short fibers), and finally effect of surface layer on impact and penetration resistance of concrete with and without steel bars reinforcement. The considered parameters in the first section were effect of fiber type and fiber volume fraction, water/cement ratio, and coarse aggregate. 0.1% and 0.2% Polypropylene fibers (fibrillated) in addition to 1.0% and 2.0% steel fibers were used in this section. The configurations of used steel fibers were straight, waved, and hooked. Two levels of water/cement ratios were considered. These ratios were 0.40 and 0.30. Pink limestone and basalt were used as a coarse aggregate. For the second section, two parameters were considered. These parameters were the effect of steel bars reinforcement ratio (1.80% and 3.6%), type of fiber and fiber volume fraction of internal short fibers. 0.1% and 0.2% Polypropylene fibers in addition to 1.0% and 2.0% steel fibers with the previous configuration were used in this section. The effect of concrete surface (1.0% steel fibrous concrete and one layer of GFRP sheets) was studied in the last section. Table 5 presents the details of used concrete mixes.

Table 1 Chemical, physical, and mechanical properties of used cement.

Chemical compositions (%)		Physical and mechanical properties	
Silicon dioxide	20.1	Percentage passing on sieve No# 170%	4
Aluminum oxide	5.1	Initial setting time (min.)	180
Ferric oxide	3.42	Final setting time (min)	315
Calcium oxide	61.1	Compressive strength of cement mortar	
		−3 days, (MPa)	18.5
Magnesium oxide	4	−7 days, (MPa)	29.6
Sulfur trioxide	2.57		
Loss on ignition	2. 75	Soundness (mm)	1
C_3A	9.8		

Table 2 Grading of coarse aggregate and sand.

Sieve size (mm)	25	19	12.5	9.50	4.75	2.36	1.18	0.60	0.30	0.15
Pink limestone	100	100	96.6	65.8	2.3	0.8	0	0	0	0
Basalt	100	100	98.8	58.6	3.4	1.20	0	0	0	0
Sand	100	100	100	100	96.2	93.4	83.2	53.3	16.1	2.0



Straight steel fibers — Waved steel fibers — Hooked steel fibers

Figure 1 Configuration of steel fibers.

Table 3 Description of steel fibers.

Steel fiber shape	Length (mm)	Equivalent diameter (mm)	Aspect ratio (%)
Straight	30–34	0.8	38–43
Hooked	50–52	0.9	56–58
Waved	50–55	0.9	56–61

2.2.2. Evaluating tests

Two evaluating tests were considered throughout this research work to evaluate the impact and penetration resistance of concrete. These tests were standard drop weight test method according to ASTM D 1557 and suggested designed simulated penetration test. 63 mm high and 150 mm diameter cylinder specimens were used for standard impact tests according to ASTM D 1557. Three specimens for each type were tested, and results referred throughout this paper will refer to the average value of three nominally identical specimens. As per ASTM D 1557, a number of blows corresponding to first crack appearance (Fc) and number of blows corresponding to failure were measured (UR). Fig. 2 shows the setup of standard impact test. Two main problems eliminate the use of this test: First, it cannot be used to evaluate the impact resistance of reinforced concrete. Second, the determination of first crack depends on the accuracy of test supervisor.

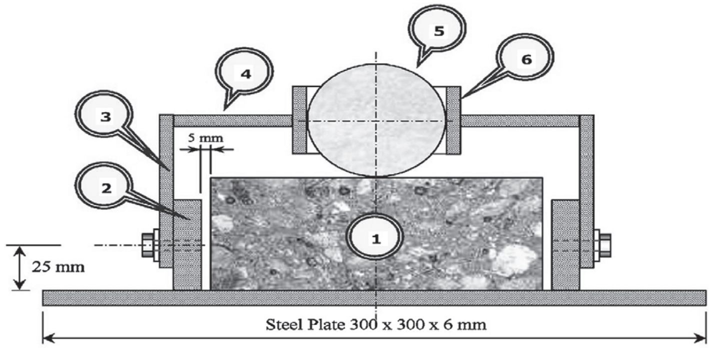
Table 4 Specifications of used GFRP.

Texture	Mass of unit area (g/m^2)	Breaking strength yarn (N/50 mm)		Count of cloth yarn (root/cm)		Fiber diameter yarn (μm)	
		Warp	Weft	Warp	Weft	Warp	Weft
Plain	200 ± 10	1300	1100	6	4	11	11

Table 5 Details of concrete mixes.

Mix No.	Type of coarse aggregate	w/c ratio	Details of fibers			Mix proportions (kg/m^3)					
			Type	Shape	Volume fraction (%)	Cement	Water	Sand	Coarse aggregate	Admixture	Fiber
1	Pink limestone	0.40	–	–	0	400	160	710	1065	4.50	0.0
2			PP	Straight	0.1	400	160	710	1060	4.90	0.9
3			PP	Straight	0.2	400	160	707	1060	5.50	1.8
4			Steel	Straight	1.0	400	160	709	1062	6.25	78.5
5			Steel	Straight	2.0	400	160	713	1077	8.50	157.0
6			Steel	Waved	1.0	400	160	708	1062	6.80	78.5
7			Steel	Waved	2.0	400	160	715	1072	8.80	157.0
8			Steel	Hooked	1.0	400	160	710	1064	6.60	78.5
9			Steel	Hooked	2.0	400	160	714	1074	8.70	157.0
10	Basalt	0.40	Steel	–	0	400	160	718	1078	4.20	0.0
11			Steel	Straight	2.0	400	160	722	1083	8.50	157.0
12		0.30	Steel	–	0	400	120	750	1124	6.50	0.0
13			Steel	Straight	2.0	400	120	750	1125	9.00	157.0

PP: polypropylene fibers.



1. Concrete specimen 150 mm Diameter &75 mm Height.
2. Steel Plate 50 x 50 x 13 mm.
3. Steel Plate 50 x 86 x 6 mm.
4. Steel Plate 50 x 6 mm.
5. Hardened Steel Ball 64 mm.
6. Steel Pipe 64 mm Diameter.

Figure 2 Impact test apparatus with the concrete disk in place.

1. Pulley.
2. Cable.
3. Guide pipe.
4. Main steel guide.
5. Steel frame (guide loader).
6. Specimen.
7. Cylindrical steel mass.
8. Projectile sharp head.
9. Steel plate (base support).
10. Hand winch.

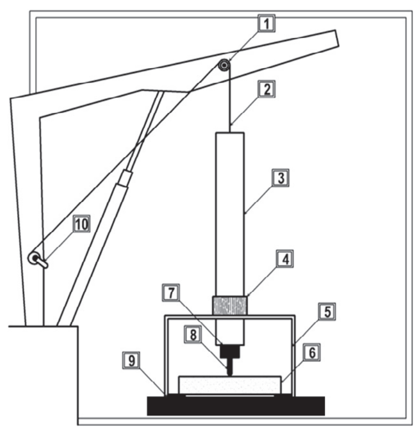


Figure 3 Penetration test apparatus.

The penetration test was conducted using simulation instrument for gas gun with a barrel of 12.7 mm in diameter and 1320 mm in length. The gun used compressed nitrogen gas an initial velocity of 108 m/s. The weight of projectile of this gun is 34 grams and its dimensions are 12.7 mm diameter and 25.4 mm length and a sharp head with a 45° angle [7,17]. The proposed test has been designed to give the same dimensions and impact energy of the original projectile. Fig. 3 shows the details of the suggested penetration test.

The test was carried out by dropping a cylindrical steel mass weighting 33 kg from a height of 610 mm. This weight and corresponding height are selected to achieve the same energy of the aforementioned gas gun. The used specimen of this test is square panel of $450 * 450$ mm and 50 mm thickness.

2.2.3. Preparation of specimens

All mix constituents were mixed together in a concrete mixer with capacity of 140 l. The coarse aggregate, cement, and sand were dry-mixed for about one minute. Mixing water and super plasticizer were added gradually during mixing. For plain concrete, the mixing process was continued for three minutes. For fiber reinforced concrete mixes, mixing was continued for three minutes before adding the fibers, which were added slowly to the mixer to avoid clumping. All contents are mechanically mixed for a further five minutes together to achieve a uniform homogeneous fresh concrete without any segregation. After mixing, fresh concrete was cast in the forms. An external mechanical vibrator was used for compacting of concrete. The specimens were stored at room temperature (20–30 °C) for 24 h and then de-mold. After that, the concrete samples were cured for 28 days in potable water. In case of reinforced specimens, the fresh concrete was cast in two layers. The first layer was cast then the steel bars were placed, and finally, the second layer of concrete was cast to achieve enough cover for the reinforcement.

The application of the concrete protective layer was embedded as follow: the first 25 mm was cast and then fixing steel shear connectors, 2.00 mm diameter and 50 mm long. The embedded part of shear connectors is 20 mm length. After fixing shear connectors, the rest concrete layer was applied.

In addition, FRP sheets were applied during concrete casting at 25 mm from the concrete surface (the same position of steel reinforcement).

3. Test results and discussions

3.1. Impact and penetration resistance of plain and fibrous concrete without steel reinforcement bars

Impact and penetration resistance of concrete were measured using two methods. The first method measured the number of blows for the first crack (FC) and the ultimate impact resistance (UR) by using the drop weight test method according to ASTM D 1557. The second method measured the penetration depth, entrance crater diameter, crack pattern, and the mode of failure of tested concrete panel using designed penetration instrument method.

3.1.1. Evaluation of impact resistance of concrete using drop weight test method according to ASTM D 1557

3.1.1.1. Effect of fibers type and content. Table 6 summarizes test results of impact resistance of concrete using ASTM D 1557 method for concrete with and without internal fibers made with pink limestone and basalt coarse aggregates at 0.40 and 0.30 w/c ratio. From Table 6, it is clear that the use of fibers either polypropylene or steel has a significant effect on impact resistance of concrete. This trend is clear on the values of number of blows corresponding to first crack occurrence and ultimate impact resistance for concrete made with pink limestone and 0.40 w/c ratio. Also, it is clear that the ability of fibrous concrete to resist the impact loads depends mainly on the type and content of the used fibers in the concrete mix. For example, the increase in number of blows corresponding to first crack is about 5% and 12%, while the increase in ultimate impact resistance is about 14% and 20% for concrete with 0.1% and 0.2% polypropylene fibers compared with concrete without internal fibers, respectively. Also, for straight steel fibers, the increase in number of blows corresponding to first crack is about 18% and 32%, while the increase in ultimate impact resistance is about 21% and 59% for concrete with 1.0% and 2.0%, respectively, compared with concrete without fibers. This may be due to the toughness enhancement [17]. This behavior agrees with Piti, Sidney, and Luo [19,2].

The shape of used steel fibers clearly affected the impact resistance of concrete where concrete mixes with hooked steel fibers has optimum values of first crack resistance and ultimate resistance compared with other types of used steel fibers. This behavior may be due to the good bond strength between hooked steel fibers and concrete which increases the toughness of concrete and impact resistance of concrete. This effect is much more significant for higher dosage of steel fibers. The aforementioned positive effect of using steel fibers also exists in concrete mixes made with basalt as a coarse aggregate as shown in Table 6.

3.1.1.2. Effect of coarse aggregate type. The effect of coarse aggregate type on impact resistance of concrete with and without steel fibers is presented in Table 6. From this table, one can conclude that the use of basalt as a coarse aggregate has a great effect on impact resistance of concrete compared with pink limestone. The increase in initial crack resistance and ultimate impact resistance as a result of using basalt compared with pink limestone is about 10% and 13% for concrete without internal fibers where this increase is about 27% and 21% for concrete with 2.0% straight steel fibers. This result agrees with Johan [6] and Dancygier [11]. They indicated that the properties of transition zone between aggregate and matrix affect the impact resistance of concrete and the coarse aggregate arrests the crack growth which produce later meandering and branching of cracks. Thus, the aggregate strength has a larger influence on the concrete impact resistance. The hardness of basalt compared with pink limestone additionally explains the positive effect of using basalt compared with pink limestone.

3.1.1.3. Effect of water/cement ratio. The effect of w/c ratio, as mentioned before, was considered for concrete made with basalt as illustrated in Table 6. The positive effect of decreasing w/c ratio is pronounced. From test results, it can be concluded that there is an increase in the number of blows that needed to achieve the first crack about 22% and about 15% for the ultimate impact resistance when water/cement ratio decreases from 0.40 to 0.30. This behavior may be due to the improvement of concrete mechanical properties and enhancement of

Table 6 Test results of impact resistance according to ASTM D 1557 test method.

Type of aggregates	w/c ratio	Details of fibers			Dropped weight test results (No. of blows)		Concrete compressive strength (MPa)
		Type	Shape	Volume fraction (%)	First crack (FC)	Ultimate resistance (UR)	
Pink limestone	0.40	–	–	0.0	74	85	35.7
		Polypropylene	Straight	0.1	78	97	36.5
		Polypropylene	Straight	0.2	83	102	36.8
		Steel	Straight	1.0	87	103	38.4
		Steel	Straight	2.0	98	135	41.7
		Steel	Waved	1.0	91	112	38.3
		Steel	Waved	2.0	109	142	42.6
		Steel	Hooked	1.0	96	113	38.8
		Steel	Hooked	2.0	115	156	42.5
Basalt	0.40	–	–	0.0	81	96	38.9
		Steel	Straight	2.0	124	163	46.2
	0.30	–	–	0.0	99	110	47.8
		Steel	Straight	2.0	135	174	55.3

transition zone characteristics. These results agree with Thabet [1] and Riedel [20].

3.1.2. Evaluation using designed simulated penetration test

Measuring the penetration depth, entrance crater area, crack width, and the mode of failure of the tested concrete panel with the designed penetration instrument were used to study the concrete behavior with different variables toward the penetration loads. These variables were fibers type and volume fraction, coarse aggregate type, water/cement ratio, and the effect of compressive strength of the concrete on the penetration resistance. Fig. 4 shows configuration of crater area and cracks on test specimen.

3.1.2.1. Effect of fibers type and volume fraction. The mean values of penetration depth in mm, entrance crater area in mm^2, and the maximum crack width in mm obtained by the penetration test after one drop are given in Table 7. From this table, it is clear that the use of 0.1% and 0.2% polypropylene fibers has insignificant effect on penetration depth, entrance crater area, and crack width compared with concrete test panel without internal fibers. This means that high velocity and high energy test, designed simulated penetration test, is insensitive to the presence of polypropylene fibers. On the contrary, the presence of steel fibers has a significant effect; hence, penetration test is sensitive to the presence of steel fibers. The use of steel fibers decreases penetration depth, entrance crater area, and crack width compared with concrete without internal short fibers. As an example, penetration depth reduction is about 16%, 22% as a result of using 1.0% and 2.0% straight steel fibers, respectively, when compared with plain concrete. These results ensure the conclusion of Luo [2], Habel [16], and Dancygier [12].

Test results also showed that the increase in steel fibers from 1.0% to 2.0% has a slightly effect on penetration depth and entrance crater area but has a clear effect on the resulting crack width. These results only partially agree with those reported by Johan and Mattias [11] who concluded that inclusion of steel fibers in concrete mix does not have any effect on the penetration depth, but only on the entrance crater area.

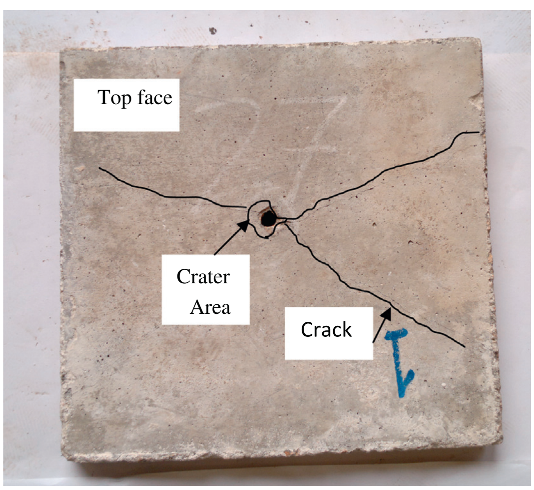


Figure 4 Configuration of crater area and cracks on test specimen.

3.1.2.2. Effect of coarse aggregate type. The effect of coarse aggregate type on impact resistance using designed simulated penetration test is presented in Table 7. From this table, it can be seen that this test is insensitive to the effect of coarse aggregate type on plain concrete. On the other hand, the effect of coarse aggregate is clear incorporate with 2.0% steel fibers where a reduction of about 15% with respect to the same mix but with pink limestone is observed. These results agree with Chanoch, Johan, and Mattias [6,11]. The positive effect of using basalt as a coarse aggregate is also evident when comparing the value of the entrance crater area. This result agrees with the conclusion of Fariborz and Joosef [7,9]. Very slight reduction in crack width (0.05 mm) was observed as a result of using basalt as a coarse aggregate instead of pink limestone.

3.1.2.3. Effect of water/cement ratio. Reduction in w/c ratio which enhances concrete properties has a significant effect either on plain and 2.0% steel fiber concrete as shown in Table 7. For example, the reduction in penetration depth is 28% and 15% for 0.0% and 2.0% steel fibers made with 0.30 w/c ratio compared with concrete mix made with 0.40 w/c ratio. The entrance crater area and crack width are also positively affected by reducing w/c ratio. These results agree with the conclusion of Piti and Badr [19,21].

Table 7 Test results of designed simulated penetration test after one drop.

Type of Aggregates	w/c ratio	Details of fibers			Designed simulated penetration test results			Crack description	Concrete compressive strength (MPa)
		Type	Shape	Content (%)	Penetration depth (mm)	Entrance crater area (mm^2)	Crack width (mm)		
Pink limestone	0.40				50	More than 500	More than 3	Full perforation	35.7
Pink limestone	0.40				50	More than 500	More than 3	Full perforation	35.7
		Polypropylene	Straight	0.1	50	More than 500	More than 3	Full perforation	36.5
		Polypropylene	Straight	0.2	47	427	2.4	Multi wide cracks	36.8
		Steel	Straight	1.0	42	403	1.3	Multi cracks	38.4
		Steel	Straight	2.0	39	385	0.6	Multi fine cracks	41.7
Basalt	0.40	–	–	0.0	50	More than 500	More than 3	Full perforation	38.9
		Steel	Straight	2.0	33	379	0.55	Fine cracks	46.2
	0.30	–	–	0.0	36	More than 500	2.50	Wide cracks	47.8
		Steel	Straight	2.0	28	344	0.30	Very fine cracks	55.3

3.2. Impact and penetration resistance of reinforced concrete with steel bars (with and without internal fibers)

3.2.1. Effect of steel bars reinforcement ratio

Effect of presence of steel reinforcement and reinforcement ratio was studied using three percentages of steel reinforcement. These percentages are 0.0% (plain concrete), 1.8%, and 3.6% (Total area of steel reinforcement/cross section area of concrete). In this section, lime stone and basalt were used as coarse aggregates, and test specimens did not include any internal short fibers. The test results of designed simulated penetration test are tabulated in Table 8. This table shows the mean values of penetration depth, entrance crater area, and the crack width obtained. Also, this table indicates the penetration depth relative to the number of drops until the failure of the concrete specimen (noted as X). From this table, it can be noticed that the steel bar reinforcement ratio has a great effect on the impact and penetration resistance of concrete. The increase in steel bar reinforcement ratio increases the number of drops corresponding to failure and decreases entrance crater area and crack width. The effect of steel bar reinforcement ratio is more evident on crack width rather than entrance crater area. For example, for concrete containing pink limestone as a coarse aggregate, the reduction in average crack width is more 42% and 77% for steel bar reinforcement ratio of 1.8% and 3.6% compared with specimens without steel bars. The positive effect of increasing steel bar reinforcement ratio may be due to the ability of reinforced concrete with steel bars to restrain, prevent the crack propagation. These results agree with Tai, Johan, Dancygier, and Zineddin [4,11,22,23].

The comparison between concrete mixes containing pink lime stone and basalt indicates that the effect of aggregate type can be neglected when percentage of steel bar reinforcement ratio is increased to 3.6%.

3.2.2. Effect of fiber type and content

The effect of fiber type and content was studied throughout this research work on reinforced concrete with 1.8% steel reinforcement ratio made with crushed pink lime stone as a coarse aggregate only. Test results obtained by the penetration test are given in Table 9. From this table, the fiber type has a significant effect on the impact resistance of reinforced concrete test panels, especially steel fibers. The use of 0.1% polypropylene fibers has insignificant effect especially on penetration depth and entrance crater area, while a clear reduction in crack width is considered.

For tested specimens with steel fibers, the increase in fibers content has a noticeable effect on number of drops at full penetration, entrance crater area, and crack width. For example, for specimens with straight steel fibers, the reduction in crack width is 49% and 66% for test panels with 1.0% and 2.0% straight steel fibers compared with specimens without internal short fibers, respectively. This trend is the same for other shapes of steel fibers. Also, from the test results given in Table 9, it appears that the shape of steel fibers has a slight effect on the impact and penetration resistance of reinforced concrete specimens. The specimens reinforced with hooked end steel fibers showed considerably better behavior when compared to other shapes of steel fibers as well as specimens reinforced with polypropylene fibers. It is anyway worth mentioning that the

Table 8 Results of penetration test for steel bars reinforced plain concrete (effect of reinforcement ratio).

Type of coarse aggregate	Reinforcement ratio (%)	Penetration depth (mm)				Entrance crater area (mm^2) at final drop	Crack width (mm)	Remarks
		Drop1	Drop2	Drop3	Drop4			
Pink limestone	0.0	X	X	X	X	More than 500	More than 3	Full damage
Basalt	0.0	X	X	X	X	More than 500	More than 3	Full damage
Pink limestone	1.8	28	X	X	X	465	1.75	Wide cracks
Basalt	1.8	23	X	X	X	451	1.4	Fine cracks
Pink limestone	3.6	12	29	X	X	443	0.7	Very fine crack
Basalt	3.6	10	21	38	X	437	0.6	Very fine crack

Note. X: full penetration.

Table 9 Results of penetration test for reinforced concrete test panels with the steel bars with 1.8% steel reinforcement ratio.

Type of fiber	Fiber volume fraction and shape	Penetration depth (mm)				Entrance crater area (mm^2) at final drop	Crack width (mm)	Remarks
		Drop1	Drop2	Drop3	Drop4			
Control	...	28	X	X	X	465	1.75	Wide cracks
Polypropylene	0.1%, polypropylene	26	X	X	X	441	1.55	Wide cracks
Polypropylene	0.2%, polypropylene	22	X	X	X	422	1.4	Wide cracks
Steel	1.0%, straight steel	16	X	X	X	387	0.9	Multi fine cracks
Steel	1.0%, waved	12	21	X	X	364	0.85	Multi fine cracks
Steel	1.0%, hooked	10	13	X	X	352	0.75	Fine cracks
Steel	2.0%, straight	9	40	X	X	331	0.6	Very fine cracks
Steel	2.0%, waved	7	19	25	39	324	0.45	Microcrack
Steel	2.0%, hooked	5	12	23	36	311	0.3	Invisible crack

Note. X: full penetration.

steel fiber ratio plays a much more significant role than the shape of steel fibers.

The previously mentioned trend is anyway seems to contradict what was found by Johan and Mattias Unosson [11] who concluded that the presence of the steel fiber in the concrete mix has no effect on the penetration depth anyway the present results coincides with those by Dancygier [22].

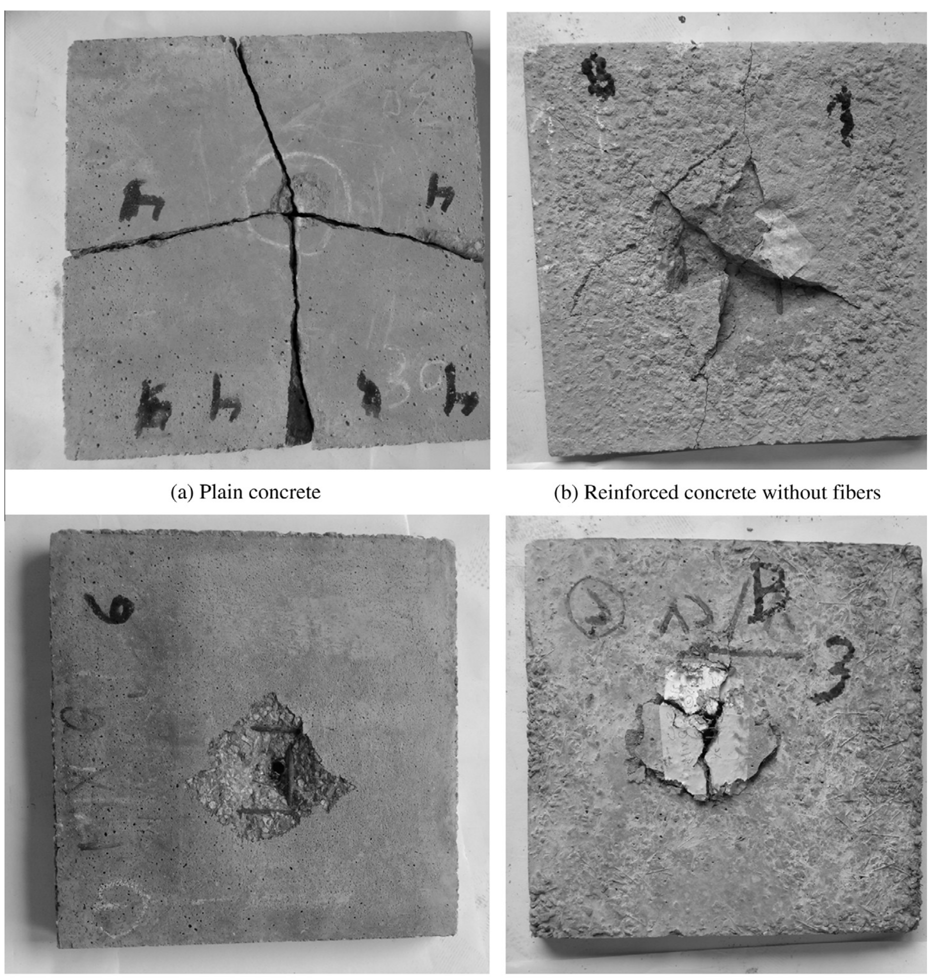
The mode of failure confirms the previous trend where the use of fibers localized damage and arrests the crack propagations especially for test panels with steel fibers as shown in Fig 5. These results coincide with results of Song [24] and Xu [25], they indicated that steel fiber is helpful in reducing the size of the damage zone.

3.3. Effect of surface layer condition on impact and penetration resistance of concrete

3.3.1. Covering with fibrous concrete

The test results obtained from the penetration tests for reinforced concrete specimens (0.40 w/c ratio and 1.8% steel reinforcement ratio made with crushed pink limestone as a coarse aggregate) which are covered with 1.0% steel fibrous concrete layer are given in Table 10. It is important to observe that the control uncovered specimen has a total thickness equal to the total thickness of covered specimens with different shape of steel fibers.

From Table 10, it can be noticed that covering concrete specimens with a protective layer reinforced with fibers featuring different shapes is very effective solution to improve the penetration resistance of concrete. As an example, after one drop, penetration depth reduction of about 25%, 26%, and 39% has been observed in the penetration depth as a result of covering the tested specimens with straight, waved, and hooked steel fibrous concrete, respectively, when compared to uncovered reinforced concrete. Finally, the present study shows that covering reinforced concrete specimens with a fibrous concrete layer with hocked shape seems to be more effective than straight and waved ones in improvement the penetration and the impact resistance of concrete. The test results of entrance crater area and crack width ensure the aforementioned behavior. Also, the final pattern of cracks features very fine to hairline cracks for concrete specimens covered with fibrous concrete compared with control specimen.



(a) Plain concrete

(b) Reinforced concrete without fibers

(c) Reinforced concrete with 0.2% polypropylene

(d) Reinforced concrete with 2% straight steel fiber

Figure 5 Mode of failure for test panel plain concrete, reinforced concrete without fibers and with 0.2% polypropylene fibers and 2.0% straight steel fibers.

Table 10 Results of penetration test for steel bars reinforced concrete covered with fibrous concrete.

Reinforced concrete type	Covering fiber type, content	Penetration depth (mm)				Entrance crater area (mm^2) at final drop	Crack width (mm)	Remarks
		Drop1	Drop2	Drop3	Drop4			
Uncovered reinforced concrete	Control	28	X	X	X	465	1.75	Wide cracks
Covered concrete	Straight steel fibers, 1%	21	31	39	X	398	0.95	Very fine cracks
Covered concrete	Waved steel fibers, 1%	20	29	37	X	376	0.9	One visible crack
Covered concrete	Hooked steel fibers, 1%	17	24	30	38	361	0.75	Hair cracks

Note. X: full penetration.

Table 11 Results of penetration test after one drop for uncovered concrete and covered concrete with FRP sheets.

Concrete type	Fiber type and volume fraction	Penetration depth (mm)	Entrance crater area (mm^2)	Crack width (mm)	Remarks
Plain concrete	...	50	More than 500	More than 3	Full perforation
Plain concrete with GFRP cover	...	43	412	1.75	Multi wide cracks
Polypropylene fibrous concrete	0.1%, p.p. fibers	50	More than 500	More than 3	Full perforation
Polypropylene fibrous concrete with GFRP cover	0.1%, p.p. fibers	40	387	1.2	Wide crack
Polypropylene fibrous concrete	0.2%, p.p. fibers	47	427	2.4	Multi wide cracks
Polypropylene fibrous concrete with GFRP cover	0.2%, p.p. fibers	39	352	1	Multi fine cracks
Steel fibrous concrete	1%, Straight steel fibers	42	403	1.3	Multi cracks
Steel fibrous concrete with GFRP cover	1%, Straight steel fibers	35	302	0.8	Fine cracks
Steel fibrous concrete	2%, Straight steel fibers	39	385	0.6	Multi fine cracks
Steel fibrous concrete with GFRP cover	2%, Straight steel fibers	32	278	0.5	Very fine cracks

3.3.2. Effect of covering with FRP sheets

One layer of GFRP sheet was used to reinforce the top layer of concrete specimens with and without internal short fibers without steel bar reinforcement. Table 11 summarizes test results of simulated penetration impact test for tested specimens as a result of one drop.

From Table 11, it can be observed that reinforcing top surface of concrete specimens with GFRP sheets represents another effective solution to improve the penetration resistance. The reduction in penetration depth after one drop is more than 14.0% as a result of using GFRP sheet on the top layer of tested specimens. This trend is the same for fibrous concrete specimens either polypropylene or steel fibrous concrete. Also, the use of one layer of GFRP yields significant reduction in entrance crater area and crack width compared with uncovered specimen. The reduction in entrance crater area as a result of using one layer of GFRP sheet is more than 17.6% compared with control specimen without GFRP sheet. This positive effect is clearer on fibrous concrete specimens reinforced with GFRP sheet on the top layer of specimens. As an example, the reduction in the entrance crater are is about 25% and 28% for 1.0% and 2.0% steel fibrous concrete specimens reinforced on the top layer with GFRP sheet compared with fibrous concrete specimens without GFRP sheet. Finally, the test results of measured crack widths further corroborate the statements above.

4. Conclusions

Based on the experimental test results which have been detailed in the paper, the following conclusions can be drawn:

1. The test results of plain and fibrous concrete, as per ASTM D1557, the use of steel fibers, with different shapes, combined with the use of basalt as a coarse aggregate, may have a significant positive effect on impact resistance of concrete.
2. The use of 0.1% and 0.2% polypropylene fibers has insignificant effect on penetration depth, entrance crater area and crack width compared with concrete test panel without internal fibers.
3. The presence of steel fibers has a significant effect on penetration depth, entrance crater area and crack width. As an example, penetration depth reduction is about 16%, 22% as a result of using 1.0% and 2.0% straight steel fibers, respectively, when compared with plain concrete.
4. Increasing steel fibers content from 1.0% to 2.0% has a slightly effect on penetration depth and entrance crater area but has a clear effect on the resulting crack width.
5. Type of coarse aggregate has insignificant effect on the impact resistance of plain concrete when it is subjected to high impact energy, as it happens in simulated penetration test, while the effect is higher incorporate with 2.0% steel fibers,
6. The presence of steel bar reinforcement enhances the impact resistance of concrete specimens. This enhancement is more evident if the crack width rather than the entrance crater area is considered.
7. Effect of aggregate type can be neglected on impact and penetration resistance of concrete at higher percentage of steel bar reinforcement ratio.

8. Shape of steel fibers has a slight effect on the impact and penetration resistance of reinforced concrete specimens. Anyway, hooked-ed fibers showed considerable better behavior compared with other shapes of steel fibers and polypropylene fibers.
9. Steel fiber ratio is more effective than shape of steel fibers on reinforced concrete specimens.
10. Concrete specimens with different shapes of steel fibrous concrete are very effective parameter on the penetration resistance of concrete and on the penetration depth. Penetration depth reduction after one drop is about 71%, 75% and 85% were observed in the penetration depth as a result of covering the tested specimens with straight, waved and hooked steel fibrous concrete, respectively.
11. Reinforcing top surface of concrete specimens with GFRP sheets represents effective solution to improve the penetration resistance. As a matter of fact, the use of one layer of GFRP yields significant reduction in entrance crater area and crack width compared with uncovered specimen.

5. Recommendations and the future work

The presented section of improving impact and penetration resistance of concrete panels as a result of improving surface properties of test panels need more studied parameters. Also, this section is considered as an introduction to strengthening of existing reinforced concrete structures by enhancement of their surface which is subjected to impact loads. These two parts are considered as research for future work.

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