Strength Evaluation of Normal Strength and Self-compacting Reinforced Concrete Beams under the Effect of Impact Loading

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Abstract: This paper is devoted to investigate experimentally the strength evaluation of normal strength and self-compacting reinforced concrete beams under the effect of impact. The experimental work includes investigating of eight ($180 \times 250 \times 1,200$ mm) beam specimens. Three variables are adopted in this paper: tensile reinforcement ratio, type of concrete (NSC (normal strength concrete) or SCC (self-compacting concrete)) and height of falling (dropped) ball (1 m or 2 m). The experimental results indicated that the number of blows increased with increasing of tensile reinforcement ratio and compressive strength by about 35% and 123%, respectively. Maximum mid-span deflection was increased with increasing falling height and decreased with increasing reinforcement ration and concrete compressive strength. The increasing of concrete compressive strength is more effective than increasing of the reinforcement ratio, it appeared that the percentage of increasing exceeds 50%. The ultimate strength is decreased with increasing the falling height for about 34%~44%.

Key words: Normal strength concrete, self-compacting concrete, reinforced concrete beam, impact.

1. Introduction

The importance of studying the behavior of structures under the influence of the impact loading comes through occurrence of earthquakes in different parts of the world, especially east of Asia, and these earthquakes cause human and materials losses.

There are many researchers is interested to study the effect of impact loading on the behavior of different structural members. Some of the researchers [1, 2] have studied the effect of impact loading on the cylinder with 152-mm diameter and 60-mm height. The main variables were the tensile strength, through adding a percentage of steel fiber, the values of compressive strength of concrete and the drop height of falling body. They found that the addition of steel fibers dosage improved the characteristic number of blows, and the numbers of blows were increased when increasing the

compressive strength of concrete.

Other researchers [3-5] have studied the effect of impact loading on the behavior of reinforced concrete slabs. They found that the falling height is effective on increasing the deflection and ultimate capacity, and the mode of failure affected mainly by drop hammer weight.

Several researchers [6-9] have studied the structural behavior of reinforced concrete columns under the influence of impact loading. They found that the concrete grade and reinforcement ratio have a profound effect on the impact capacity of columns, while the confinement of column enhanced the impact capacity.

The other numbers of researchers [10-15] were interested in studying the effect of impact loading on the behavior of reinforced concrete beams, and most of them have reached to similar conclusions. They concluded that the load carrying capacity, the energy dissipation and displacement values increased with increasing falling height and the mode of failure depended mainly on flexural reinforcement and

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compressive strength of concrete.

2. Experimental Program

Tests were carried out on eight rectangular-section, simply supported beams under impact loading. The tested beams are reinforced in longitudinal direction (flexural reinforcement) and transverse direction (shear reinforcement). Three variables are adopted in this paper, tensile reinforcement ratio at the bottom of the beams section, type of concrete (NSC (normal strength concrete) or SCC (self-compacting concrete)) and the height of falling (dropped) ball (1 m or 2 m) (Tables 1 and 2). While, the sectional area, length, top reinforcement and shear reinforcement are kept constant for all tested beams. Also, a series of tests were performed on concrete mixes, therefore, the mechanical properties of hardened concrete and fresh concrete tests were included in this paper.

3. Beam Specimens Details

The nominal dimensions and the details of tested beams are shown in Figs. 1 and 2. The overall length of beam specimens was 1,200 mm, while the overall depth and width were 250 mm and 180 mm, respectively. In this study, two types of tensile

reinforcement ratio were adopted as a variables, four beam specimens were reinforced with $2\phi 12$ mm deformed bars, while the others were reinforced with $3\phi 12$ mm deformed bars. All beam specimens were reinforced with $2\phi 12$ mm deformed bars at the top and $\phi 6$ mm @150 mm deformed bars as shear reinforcement. Table 1 shows the details and designation of tested beams.

4. Materials

In manufacturing the tested specimens, local construction materials are used (except steel bars), description of materials properties are reported and presented in the following sections.

4.1 Cement

Chemical and physical properties and description of the used cement are reported and presented in Tables 3 and 4. The tests were carried out according to ASTM (American Society for Testing and Materials) C-150 [16].

4.2 Fine Aggregate

Fine aggregate with maximum size less than 5.0 mm are used in this study. Test results and specifications of the fine aggregate are shown in Tables 5 and 6.

Table 1 Beams designation and details.

Beam designation	Dimensions (mm)			Reinforcement			Concrete type
				Flexural		Shear	
	b_w	h	l	Bottom	Top		
B1*	180	250	1,200	2 ϕ 12	2 ϕ 12	ϕ 6 mm @150 mm	NSC
B2				3 ϕ 12			NSC
B3				2 ϕ 12			SCC
B4				3 ϕ 12			SCC
B-5				2 ϕ 12			NSC
B6				3 ϕ 12			NSC
B7				2 ϕ 12			SCC
B8				3 ϕ 12			SCC

*Reference beam.

Table 2 Height of falling (dropped) ball.

Beam designation	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8
Falling height (m)	1.0	1.0	1.0	1.0	2.0	2.0	2.0	2.0

Fig. 1 Details of tested beams: B1, B3, B5 and B7.

Fig. 2 Details of tested beams: B2, B4, B6 and B8.

Table 3 Chemical composition of cement.

Chemical composition	Percentage by weight (%)
CaO	56.6
SiO ₂	23.92
Al ₂ O ₃	6.7
Fe ₂ O ₃	3.03
MgO	3.23
SO ₃	1.87
L.O.I	1.9
I.R	0.89
L.S.F	0.86

Table 4 Physical properties of cement.

Physical properties	Test result
Fineness (kg/m^2)	2,820
Soundness	0.22%
Initial setting time (min)	159
Final setting time (min)	232
Compressive strength (3 days) (MPa)	10.1
Compressive strength (7 days) (MPa)	16.9

Table 5 Grading of fine aggregate.

No.	Sieve size (mm)	Percentage of passing (%)	BS (British Standards) 882: 1992 limit zone "M" (percentage of passing (%)) [17]
1	5	94.66	89~100
2	2.36	81.89	65~100
3	1.18	58.72	45~100
4	0.6	66.83	25~80
5	0.3	31.33	5~48
6	0.15	7.61	0~15

Table 6 Physical properties of fine aggregate.

Property	Test result
Water absorption	0.52%
Specific gravity	2.47%
Fineness modulus	2.78%
Moisture content	0.23%

4.3 Coarse Aggregate

Coarse aggregate used in this study has maximum size less than 10 mm. 100% crushed aggregate with a minimum of flat and elongated particles is used. Table 7 shows the grading of coarse aggregate.

4.4 Steel Reinforcement

Tensile test of steel reinforcement is carried out on $\phi 12$ mm and $\phi 6$ mm hot rolled, deformed, mild steel bar employed as flexural reinforcement, and $\phi 6$ mm deformed mild steel bar was used as shear reinforcement. Table 8 shows the results of tensile tests for steel bars.

4.5 Limestone Powder

Limestone powder has been used as a filler for concrete production for many years ago. Limestone powder has been found effective to increase workability and early strength, as well as to reduce the required compaction energy. The increased strength is

found particularly when the powder is finer than the Portland cement particles [19].

A fine limestone powder (locally named as Al-Gubra) with fineness of $3,100 \text{ cm}^2/\text{gm}$ is used to avoid excessive heat generation, enhance fluidity and cohesiveness, improve segregation resistance and increase the amount of fine powders in the mix (cement and filler).

According to EFNARC (European Federation Dedicated to Specialist Construction Chemicals and Concrete Systems) [20], the fraction less than 0.125 mm will be of most benefit. The chemical composition of LSP (limestone powder) is listed in Table 9.

4.6 Superplasticizer

To produce self-compacting concrete, superplasticizer known as HWRA (high water reducing agent) based on polycarboxylic-ether is used. It has the trade mark Glenium-51. Glenium-51 is free from chlorides and

complies with ASTM C494 [21] Types A and F. It is compatible with all Portland cements that meet recognized international standards. Table 10 shows the typical properties of Glenium-51.

4.7 Concrete Mix Design

Two concrete mixes are used in this study. The concrete mixes proportions are presented in Table 11. It was found that the used mixes produce a good workability and uniform mixing of concrete without segregation.

5. Test Procedure

Eight reinforced concrete beams were tested by exerting an impact load repeatedly until failure. Impact tests were conducted using an impact test rig which was designed and manufactured to satisfy the requirements of the experimental program. The tested beams were setup on the supports with especially designed devices allowing it to rotate while preventing it from moving out of displacement. Each reinforced concrete beam was clamped on its top and bottom

Table 7 Grading of coarse aggregate.

No.	Sieve size (mm)	Present work of coarse aggregate (percentage of passing)	BS 882: 1992 limit (percentage of passing) [17]
1	20	100	100
2	14	100	90~100
3	10	79.5	50~85
4	5	6.5	0~10
5	2.36	0	0

Table 8 Properties of steel bars.

Nominal diameter (mm)	Bar type	f_y^* (MPa)	f_u (MPa)	E_s^{**} (GPa)	Elongation (%)
6	Deformed	380	545	200	11
12	Deformed	420	653	200	16

*Average of three specimens: 400-mm length; **ACI (American Concrete Institute) 318M-11 [18].

Table 9 Chemical composition properties of L.S.P.

Oxides	Percentage (%)
Calcium oxides CaO	56.10
Silicon oxides SiO ₂	1.38
Aluminum oxides Al ₂ O ₃	0.72
Ferric oxides Fe ₂ O ₃	0.12
Magnesium oxides MgO	0.13
Sulphur trioxides SO ₃	0.21
Loss on ignition L.O.I	40.56

Table 10 Typical properties of Glenium-51*.

Commercial name	Glenium 51
Chemical composition	Sulphonated melamine and naphthalene formaldehyde condensates
Subsidiary effect	Increased early and ultimate compressive strength
Form	Viscous liquid
Color	Light brown
Relative density	1.1 g/cm ³ @20 °C
pH	6.6
Viscosity	128 N s/m ² 30 centipoises @20 °C
Transport	Not classified as dangerous
Labeling	Not hazard label required
Chlorides	Free from chlorides

*Supplied by the manufacturer.

Table 11 Details of design mixes.

Mix designation	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Water (kg/m ³)	Limestone (kg/m ³)	Superplasticizer percentage by the weight of the cement
NSC*	385	517	1155	175	-	-
SCC**	342	635	1085	175	165	5%

*Reference mix: normal strength concrete; **Reference mix: self-compacting concrete.

Fig. 3 Schematic diagram of the falling mass system (unit in mm).**Table 12 Mechanical properties of concrete.**

Property (MPa)	Value (MPa)	
	NSC	SCC
Cube compressive strength (f_{cu})*	30	60

*Average of three samples.

Table 13 Properties of the SCC in the fresh state.

Mix designation	Slump flow by Abrams cone	L-box	T-50 (sec) slump flow
SCC	720	0.86	3.6

surfaces at a point of 100 mm from the ends. Impact test was conducted by a steel cylindrical mass of 7.5 kg. Fig. 3 shows a schematic diagram of the falling mass and the falling mass system.

6. Results and Discussion

6.1 Test Results of Control Specimens

Test results of mechanical properties of control specimens (compressive strength) are summarized in Table 12. Compressive strength for cubes (f_{cu}) was carried out on concrete in accordance with BSI (British Standards Institution) 881-116 [22] with

standard cubes of 150 mm³. The cubes were loaded uniaxially by the universal compressive machine up to failure.

Three main tests were conducted on the fresh SCC which indicated for the filling ability, passing ability and segregation resistance according to EFNARC 2002 [20] and ACI 237R-07 [23]. Test results of SCC in the fresh state are summarized in Table 13.

6.2 Number of Blows versus Deflection Curves

At each test, the beam specimens were subjected to several blows from heights of 1,000 mm or 2,000 mm

till the failure. The number of blows versus mid span deflection curves for all beams are shown in Figs. 4-11. As shown in Figs. 4-11, the number of blows versus deflection curves are similar for all beams at the early stages of loading until the first cracks. After that, the deflections at mid-span show clear difference between them which indicated to behavior of each beam in a certain manner. In general, the beams' behaviors under the influence of drops have a linear behavior from the starting of load application up to appearance of first crack. At this point, the applied moment exceeds cracking moment.

There is a second linear stage follows the first crack appearance up to yielding of the reinforcement steel. The final stage of the beam behavior is a non-linear stage which starts after yielding of reinforcement steel up to failure.

6.3 Impact Response

Through studying the relationship between the number of blows and mid-span deflection, it can be seen that the deflection increases with increasing of the number of blows due to decreasing of beam stiffness through increasing the loads.

Fig. 4 No. of blows—deflection curve of beam (B1).

Fig. 5 No. of blows—deflection curve of beam (B2).

Fig. 6 No. of blows—deflection curve of beam (B3).

Fig. 7 No. of blows—deflection curve of beam (B4).

Fig. 8 No. of blows—deflection curve of beam (B5).

Fig. 9 No. of blows—deflection curve of beam (B6).

Fig. 10 No. of blows—deflection curve of beam (B7).

Fig. 11 No. of blows—deflection curve of beam (B8).

It has been observed that the number of blows increased with increasing of tensile reinforcement ratio and compressive strength by about 35% and 123%, respectively. Increasing the amount of reinforcement and concrete compressive strength have lead to the increase of depth of neutral axis from the top of the section, normally this leads to the increase of moment of inertia then the increase of flexural rigidity (EI) for specimens with high reinforcement ratio and compressive strength more than the others. Also, based on the same previous reason, the maximum deflection decreased with increasing the reinforcement ratio and concrete compressive strength (Table 14).

Increasing of falling height leads to the failure to be commenced faster in control specimen with more mid-span deflection.

At the failure, the maximum mid-span deflection increased with increasing the falling height. This increasing belongs to that the strain energy of the specimen is in the maximum value, while the kinetic energy of the falling body to be in the lowest value. So, the energy dissipation in the reinforcement and concrete decreases to the lowest level. This is the

reason for high deformation when increasing the height of falling body.

6.4 Crack Pattern and Failure Mode

The crack pattern is investigated by visual observation. All tested beams were failed by flexural cracks with circular crushing at the top surface of the beams section, and then extended towards the bottom surface as shown in Figs. 12-19.

It is observed that the first cracking load was affected by tensile reinforcement ratio and concrete compressive strength. For Beam Specimen B1, the first cracking is observed after 9 blows, but when the reinforcement ratio increase, in Beam Specimen B2, the first crack is observed after 11 blows. For Beam Specimens B3 and B4, the first cracks appeared after 18 and 22 blows, respectively. It is seen from the experimental work that the increasing of concrete compressive strength is more effective than increasing of the reinforcement ratio. It appeared that the percentage of increasing exceeded 50%, 50%, 250% and 150% in Beam Specimens B1, B2, B5 and B6, in comparison with Beam Specimens B3, B4, B7 and B8,

Table 14 Maximum deflection at failure of tested specimens.

Beam designation	B1	B2	B3	B4	B5	B6	B7	B8
Maximum deflection at failure (mm)	4.17	2.11	1.87	2.1	4.9	2.75	2.71	2.67

Fig. 12 Crack pattern of beam (B1).

Fig. 13 Crack pattern of beam (B2).

Fig. 14 Crack pattern of beam (B3).

Fig. 15 Crack pattern of beam (B4).

Fig. 16 Crack pattern of beam (B5).

Fig. 17 Crack pattern of beam (B6).

Fig. 18 Crack pattern of beam (B7).

Fig. 19 Crack pattern of beam (B8).

Table 15 First observed cracks of tested specimens.

Beam designation	B1	B2	B3	B4	B5	B6	B7	B8
First observed cracks (No. of blows)	9	11	18	22	4	6	14	15

Table 16 Maximum number of blows capacity of tested specimens.

Beam No.	B1	B2	B3	B4	B5	B6	B7	B8
Ultimate capacity (No. of blows)	17	23	38	46	10	15	21	29

respectively. Unlike the appearance of first cracks in the case of 2.0 m falling height, the first crack appeared after 4, 6, 14 and 15 blows for Beam Specimens B5~B8, respectively. The difference in the appearance of the first cracks is may be due to the stresses in the concrete have reached its allowable stress ($0.45f_c'$). In other words, the loads on the beams lead to produce an internal moment more than the cracking moment (M_{cr}). Table 15 shows the first observed cracks of the tested specimens.

6.5 Ultimate Capacity of Beam Specimens

The ultimate capacity of tested beam specimens is affected by concrete type, tensile reinforcement ratio and falling height. The ultimate capacity is increased with increasing the compressive strength about 123% for Beam Specimen B3 in comparison with the Beam Specimen B1 which has a compressive strength of

70 MPa and 30 MPa, respectively. Same manner can be seen in Beam Specimens B5 and B7 which have an increasing for about 110%.

Effectiveness of increasing the tensile reinforcement ratio can be seen clearly in Beam Specimens B2 and B6 in comparison with Beam Specimens B1 and B5, respectively, which have an increase in ultimate capacity for about 35.29% and 50%, respectively.

Unlike the previous cases, the ultimate strength is decreased with increasing the falling height for about 41%, 34%, 44% and 37% for Beam Specimens B5, B6, B7 and B8 in comparison with Beam Specimens B1, B2, B3 and B4, respectively. It may be noted that the impacting speed depends mainly on the head of falling as shown in the Eq. (1):

$$v = \sqrt{2gh} \quad (1)$$

where, h is the falling height and g is the acceleration.

Table 16 shows the maximum number of blows capacity of tested specimens.

7. Conclusions

The number of blows increased with increasing of tensile reinforcement ratio and compressive strength by about 35% and 123%, respectively. Maximum mid-span deflection was increased with increasing falling height and decreased with increasing reinforcement ration and concrete compressive strength.

The increasing of concrete compressive strength is more effective than increasing of the reinforcement ratio, it appeared that the percentage of increasing exceeded 50% in beam specimens made with NSC in comparison with beam specimens made with SSC.

The ultimate strength is decreased with increasing the falling height for about 34%~44% for beam specimens made with SSC in comparison with beam specimens made with NSC.

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