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Research Article

Effect of dimensions of specimens on the impact performance of concrete

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ABSTRACT

Mechanical properties of concrete are size dependent. While many reports have discussed the size effect of the test specimen on the static properties of concrete, research on the effect of cross-sectional dimensions of the concrete beams on its impact performance is still scarce. This research experimentally evaluates the relationship between the cross-sectional dimensions and orientation of the concrete beam specimens on their impact performance. Repetitive drop-weight test was used to evaluate the impact energy absorption capacity of different concrete beams. A loading protocol to evaluate the impact energy of concrete beams having different cross-sectional dimensions was proposed. The results revealed that the impact performance of concrete is size dependent. Strong proportional relationships between the moment of inertia, cross-sectional area and impact energy were found. As the moment of inertia and cross-sectional area of the test specimen increase, its impact energy exponentially increases. Furthermore, a linear proportional relationship was found between the normalized impact energy and the normalized cross-sectional area × moment of inertia. This means that the impact performance of concrete beams depends on both their cross-sectional area and orientation. The proposed loading protocol has been proven to be able to accurately evaluate the impact energy of concrete specimens with significantly varying impact performance while importantly saving time.

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1. Introduction

Cement-based materials are the most used materials in the building industry. Global demand on such materials production is expected to further increase due to the increasing infrastructure development (Arif et al. 2020; Döndüren and Al-Hagri 2022). Understanding the properties of concrete under different conditions is critical to understand the behavior of buildings under various critical loading conditions. One of the most critical loading conditions that a structure might be subjected to is the impact loading condition. Impact load is a medium to high-strain rate type of loading that happens over a very short period. The criticality of the loading condition increases as its loading velocity, and accordingly strain rate, increases. During the impact actions, a huge amount of energy is imparted on the structure. This might lead to catastrophic results. This type of load might be created by many sources such as explosions, ballistic projectiles, and collisions of objects (Al-Hagri et al. 2024). Behavior of concrete under impact loads is the least understood compared to its behavior under other loading conditions. Since concrete is a strain-rate material, its properties under static loading cannot be directly used to evaluate its behavior under impact loading. While under static loads cracks tend to propagate through the weakest paths, under impact loads cracks might propagate through strong zones such as aggregate particles.

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Some concrete properties such as mechanical properties are size dependent. This means that as the size of the test specimen changes, the obtained strength of concrete changes too. For this reason, standards usually specify the size of the test specimen that should be used to evaluate certain static properties of concrete. However, standards don't provide much information regarding the specimen size that should be used to evaluate the impact performance of concrete, especially under flexural impact loading. This is why different sizes of specimens have been used in literature to evaluate the impact performance of concrete. However, it is thought that change in the dimensions of the specimen might result in a change in the obtained results. Some examples of the used dimensions for beam specimens to evaluate the impact performance of concrete are presented in Table 1.

Table 1. Some examples of used beam specimen dimensions to evaluate impact strength of concrete.

Width (mm)	Height (mm)	Length (mm)	Loaded span (mm)	Reference
100	100	400	300	Cao et al. (2018); Wu et al. (2015); Yoo et al. (2015); Yu et al. (2025)
100	100	400	350	Zaki et al. (2021)
100	100	500	400	Al-Tayeb et al. (2012); Reda Taha et al. (2008)
80	100	400	300	Al-Hagri and Döndüren (2023, 2025); Bin Cai et al. (2024); Döndüren and Al-Hagri (2023)
70	70	260	210	Abid et al. (2021)
150	150	710	590	Kantar et al. (2011); Yılmaz et al. (2014)
100	50	400	300	Al-Tayeb et al. (2013a, 2013b)
50	50	750	690	Demirhan et al. (2019)

Although the size effect of concrete specimen on the static properties of concrete has been previously investigated by many studies such as (Brake et al. 2016; del Viso et al. 2008; Jiang et al. 2024; Mena-Alonso et al. 2024; Narayanan 2024; Visairo-Méndez et al. 2019; Yoo et al. 2016; Yu et al. 2025; Zi et al. 2014), only a limited number of studies have discussed the effect of dimensions of specimens on the impact performance of concrete. Li et al. (2018) investigated the specimen size effect on the compressive dynamic strength of concrete cylinders and cubes. The results showed that impact strength of concrete is affected by the size and shape of the test specimen. Lee et al. (2015) investigated the effect of cylinder size on the dynamic modulus of elasticity and compressive strength of concrete. They found that while the size of specimen didn't have a remarkable effect on the static and dynamic compressive strength and modulus of elasticity of normal strength concrete, it had a high effect in the case of high strength concrete. Krauthammer et al. (2003) and Elfahal et al. (2005) studied the size effect of normal strength and high-strength concrete cylinders respectively on the compressive impact strength of concrete. Their results showed that the behavior of concrete under impact loading is size dependent and is different from that known for static loading.

When the literature was explored, it was found that studies on the effect of dimensions of specimens on the impact behavior of concrete are very limited. Moreover, most of the published reports have focused on the size effect of cylindrical specimens on the compressive impact strength of concrete. However, according to (Bindiganavile and Banthia 2006), the flexural response of plain concrete is more size dependent than the compressive response under static and dynamic loading. Up to the best knowledge of the authors, only three studies could be found in the literature (Bindiganavile and Banthia 2006; Murali et al. 2022; Yoo and Banthia 2017) on the effect of dimensions of the concrete beams on their flexural impact strength. In all these studies, only three different sizes of prismatic beams were examined. By Murali et al. (2022), the impact behavior of preplaced aggregated fibrous concrete beam specimens having dimensions of 100×100×400 mm^3, 50×50×250 mm^3, and 150×150×550 mm^3 was investigated. By Yoo and Banthia (2017), the effect of beam dimensions (50×50×250 mm^3, 100×100×400 mm^3, 150×150×550 mm^3) on the impact strength of ultra-high-performance fiber-reinforced concrete beams was evaluated. By Bindiganavile and Banthia (2006), prismatic concrete beams with different dimensions (50×50×450 mm^3, 100×100×350 mm^3, 150×150×500 mm^3) were tested under drop-weight test. However, in the later study, repetitive impact test was not considered. This highlights the necessity of the current study.

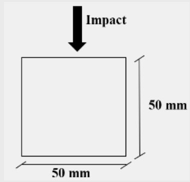
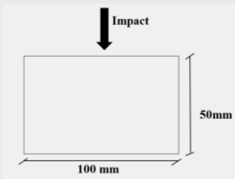
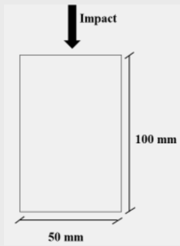
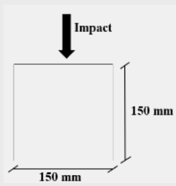
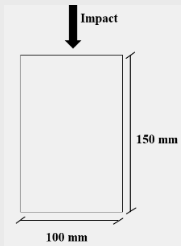
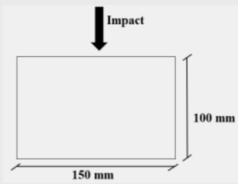
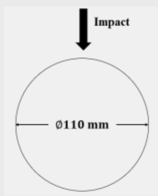
In the current study, the effect of dimensions and orientation of concrete beams having different shapes (prismatic and cylindrical) on the impact performance of concrete have been experimentally evaluated using drop-weight test. Seven different beam cross-sectional dimensions and orientations have been examined. The relationship between moment of inertia (I), cross-sectional area (A), and impact energy (E) has been investigated. Moreover, a loading protocol to evaluate the impact performance of concrete specimens having varying sizes have been proposed and evaluated.

2. Experimental Program

2.1. Preparation of specimens

To evaluate the size effect of concrete specimens on the impact strength of concrete, concrete beams having different dimensions were produced. While the length of the concrete specimens was kept constant as 400 mm, the width (b) and the height (h) of the beams were changed. All beams have a loaded span of 300 mm. Seven different cross-sectional dimensions were evaluated within the scope of this study. All produced concrete beams were tested using drop-weight test. Details of the evaluated beam specimens are shown in Table 2.

Table 2. Details of the test specimens.

Specimen code	Specimen type	Dimensions (h×b×L) (mm)	Section orientation
S50×50	Prismatic	50×50×400	
S50×100	Prismatic	50×100×400	
S100×50	Prismatic	100×50×400	
S150× 150	Prismatic	150×150×400	
S150×100	Prismatic	150×100×400	
S100×150	Prismatic	100×150×400	
S110	Cylindrical	110×400	

As can be seen from the table, prismatic beam specimens having six different width and height dimensions ranging from 50 mm to 150 mm were tested. Moreover, cylindrical beam specimens having a diameter of 110 mm were also evaluated. On average three samples were prepared and tested for each different cross-sectional size. It can be seen from the table that a unique specimen code was assigned to each group of specimens according to their cross-sectional dimensions.

In the code, the first number refers to the height of the specimen while the second one represents the width. For the cylindrical specimens, only one number representing the diameter of the cross-section was used.

In order to experimentally determine the compressive strength of concrete, three cylinders having a height of 300 mm and a diameter of 150 mm were also produced. After 24 hours of pouring the concrete into the proper molds, test specimens were demolded and put inside the curing tanks as presented in Fig. 1(a). All samples were tested after 28 days. The prepared test samples are shown in Fig. 1(b).

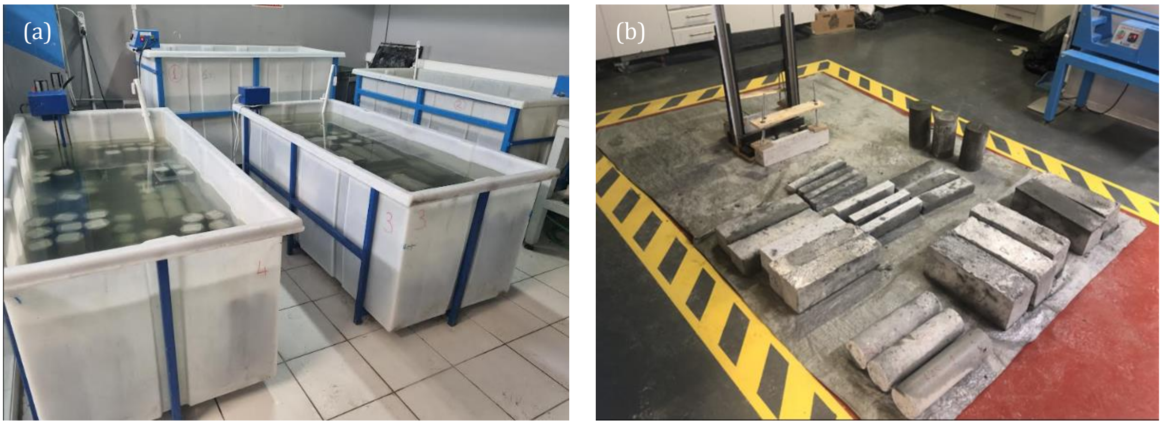


Fig. 1. Test specimens: (a) Inside the curing tanks; (b) After the curing process.

2.2. Procedure and testing

The impact strength of concrete beam specimens was evaluated using drop-weight impact test. For this reason, a proper drop weight impact test device was produced first. Some images of the production process of the device are presented in Fig. 2. Details of the prepared impact test device is shown in Fig. 3(a). The test device consists of two rails made of frictionless steel linear shaft having a high wear resistance and covered with chrome. The total length of the rails is 1 m each and the diameter is 25 mm. The shafts are tied to aluminum plates that support the rails and can be used for connection purposes. The rails are connected to a wooden frame that is used as support. To connect the impact hammer to the linear shafts, two bearings were used at the sides of the impact hammer. These bearings help minimize the loss of energy due to friction while allowing the impact hammer to move freely in the vertical direction. Considering the height of the test samples and the height of the hammer impact tip, an impact height of up to 70 cm can be obtained.

Impact hammers having different weights can be attached to the test unit. Since the impact performance of the prepared concrete beams was expected to greatly vary between the beams with small cross-sections and the bigger ones, two steel impact hammers were initially prepared. The weight of the smaller hammer is 1.49 kg, while the weight of the heavier one is 3.09 kg. The diameter of the impact tip of these impact hammers is 15 mm and 24 mm respectively. During the tests, it was found that bigger beams necessitated a heavier impact hammer, for this reason, extra weights were attached to the 3.09 kg impact hammer to increase its weight up to 5.20 kg. The used impact hammers are shown in Fig. 3.

To stop the test specimens from overturning and movement during the test, two reinforced concrete beams were produced and used as supports. As can be seen from Fig. 3, two threaded tie rods are put at each end of each RC beam. Using a proper wooden piece at each side, the samples are held tight in their position during the impact test.

The impact performance of the concrete beams was evaluated using the cumulative impact energy (E). The impact energy is calculated as $E = \sum mgh$, where m is the impact hammer weight (kg), g is the gravitational acceleration (9.81 m/s^2), and h is the impact height (m). The average impact energy of three specimens was calculated and reported.

Since a great variance between the impact energy of the smaller and bigger concrete beams is expected, and to save time, a proper loading protocol should be used. For this purpose, the following loading protocol was proposed. This loading protocol depends on gradually increasing the potential impact energy until failure of the sample. The potential impact energy was increased by gradually increasing the impact height first and then by increasing the impact weight. At first, the lighter impact hammer was used to hit the samples from a height of 10 cm for a maximum of 10 drops. If the sample passes this loading step and didn't fail, the impact height was increased by 10 cm. The impact test continued for a maximum of another 10 drops. If the samples pass this loading step too, the impact height was increased by another 10 cm. The process continued until the maximum impact height (i.e., 70 cm) was reached. After that, the lighter impact hammer was replaced by the 3.09 kg hammer. Impact test continued from a height of 10 cm. After that, the impact height was increased by 10 cm at each step. A maximum of ten impacts were used in each step. When the maximum height was reached again, the impact process continued for 100 hits in this loading step. If the sample didn't fail within this process, extra weight was added to the 3.09 kg impact hammer to increase its weight to 5.20 kg. The impact test then continued by using this heavier impact hammer from a height of 70 cm until the complete fracture of the sample. This loading protocol was used considering the loading protocols reported in (Cao et al. 2022; Hrynyk 2013), where the applied impact energy was changed during the impact test of RC specimens. This type of loading protocol is believed to better evaluate the impact performance of samples with greatly varying impact capacities while importantly saving time.

Fig. 2. Production of the impact test device.

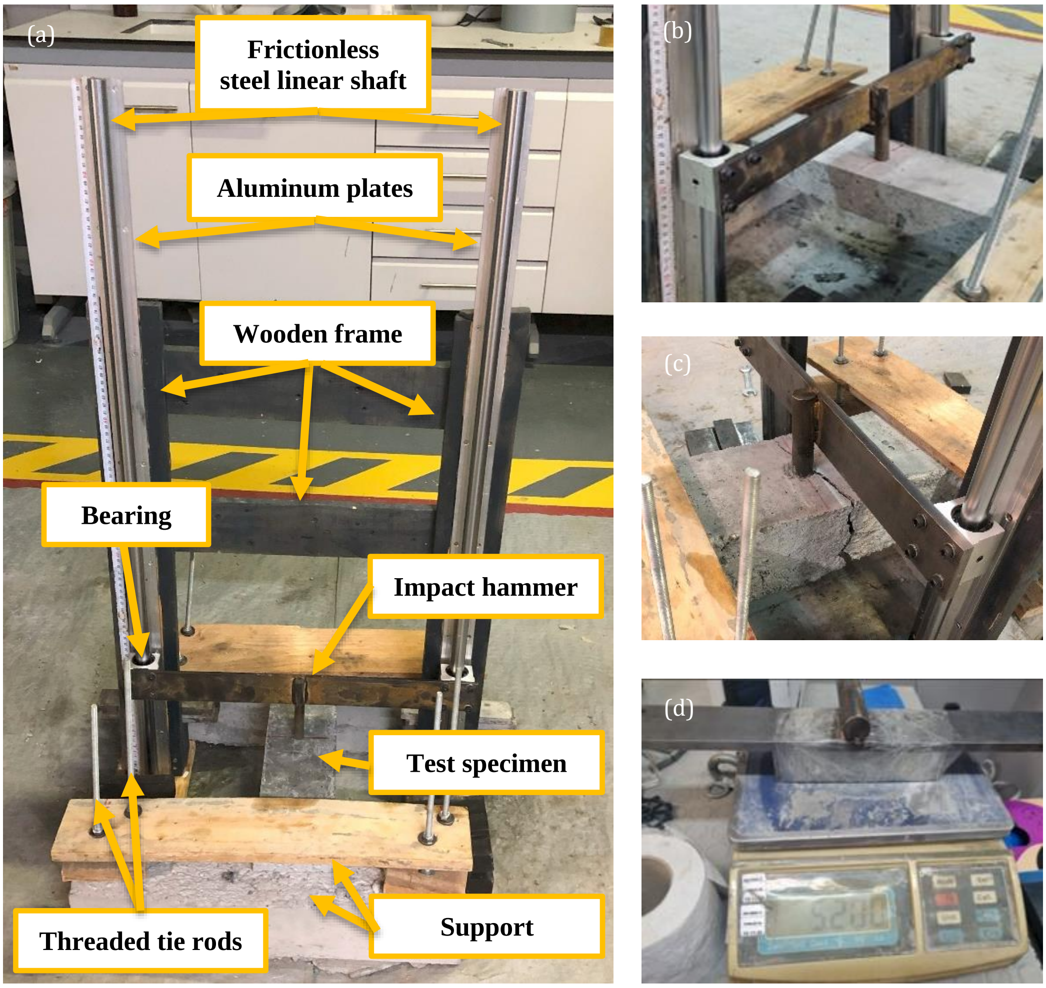


Fig. 3. Impact test set-up:
(a) drop-weight test device; (b) 1.49 kg impact hammer; (c) 3.09 kg impact hammer; (d) 5.20 kg impact hammer.

3. Results and Discussion

The compressive strength test (Fig. 4) was performed using three cylindrical samples. The average compressive strength was found to be 43.74 MPa. Repetitive drop-weight impact test (Fig. 5) was used to evaluate the impact strength of concrete beam specimens. The test results are presented in Table 3. In the table, the average impact energy of concrete beams was reported. It was found that all the tested samples showed a brittle failure. This means that the samples fractured directly without showing any visible cracks before failure. It also means that they did not show any elasto-plastic behavior. This brittle failure was found for all the tested samples, regardless of their sizes and shapes. Some images of fracture samples after the end of the impact test are presented in Fig. 6.

It's worth mentioning that this brittle behavior under impact loading can be shifted to a more ductile one by the incorporation of some additive materials into concrete such as fibers (Al-Hagri and Döndüren 2025) and tire rubbers (Döndüren and Al-Hagri 2023). It's also worth mentioning that not all additive materials have this capability. Some additive materials such as nano additives don't change the brittle behavior of concrete (Al-Hagri and Döndüren 2023).

Fig. 4. Compressive strength test of concrete.

Fig. 5. Impact test of concrete.

Table 3. Impact test results

Specimen code	Moment of inertia (I) (cm^4)	Cross-sectional area (A) (cm^2)	Impact energy up to failure (N·m)
S50×50	52.1	25	48.24
S50×100	416.7	50	26.31
S100×50	104.2	50	65.78
S150×150	4218.8	225	35,126.77
S150×100	2812.5	150	2,997.99
S100×150	1250.0	150	4,953.17
S110	718.7	95	43.85

Fig. 6. Fractured test samples.

The results revealed that while small impact hammer (1.49 kg) was sufficient to break samples with moment of inertia less than 750 cm^4 and cross-sectional area less than 100 cm^2, samples with higher A and I necessitated a higher weight to save the experimental time. In this case, the heavier impact hammer 3.09 kg was used. Moreover, some samples such as (S150×150 and S100×150) required an even heavier impact hammer. This is why during the test the authors attached extra weight to the 3.09 kg hammer increasing its weight to 5.20 kg. This indicates the efficiency of the proposed loading protocol. It is thought that using of the lighter weight hammer (1.49 kg) from a height of 10 cm would have necessitated a huge number of impacts to fracture the bigger beams. For example, if this loading step is the only one that is used for fracturing S150×150 beams, more than 24000 drops might have been necessary to produce the 35126.77 N·m impact energy that is necessary to fracture the samples. Which would have necessitated a lot of time to be achieved. On the other hand, if the heavy weight hammer (5.20 kg) from a height of 70 cm was used for all the beams specimens, samples with small cross- sectional dimensions might have failed from the first impact drop. This means that the impact energy of these small samples would have been inaccurately evaluated. This is a clear indication of the efficiency of the proposed loading protocol in accurately evaluating the impact performance of samples with different impact performances while remarkably saving experimental time.

It should be noted that there are some impact tests that can be used to evaluate the impact performance of concretes having varying impact performance such as the Charpy impact test. However, the Charpy impact test unit is much more expensive than the impact test device manufactured and used in the current study. The drop-weight test device used in this study costs approximately USD $50, which can be afforded by most research teams if not all. Moreover, this test device is very easy to manufacture. The loading protocol adapted in the current study can add up to the cost efficiency advantage of the drop-weight impact test device by making it efficient to test concretes with remarkably varying impact performances. Accordingly, a cost-efficient simple test procedure can be used to evaluate the impact performance of such concretes. A comparison between the proposed loading protocol and the use of the Charpy impact test can be investigated in future research.

As can be seen from Table 3, the impact performance of concrete is a size dependent property. To evaluate this relationship, the relationship between the impact energy and the moment of inertia is graphically presented in Fig. 7. As can be seen from the figure, the impact performance of concrete increased as the moment of inertia increased. Increasing the moment of inertia of the member increases its stiffness and toughness and accordingly its impact absorption capacity (Al-Hagri et al. 2024). An exponential relationship between the moment of inertia and the impact energy was found. The coefficient of determination (R^2), which gives an idea about the quality of the found relationship, has a very high value of 0.98. When the value of R^2 gets higher than 0.7, it represents a high-quality relationship. The higher the value is the higher quality it is (Al-Hagri and Döndüren 2025; Döndüren and Al-Hagri 2023; Gupta et al. 2015; Nakipoglu et al. 2022; Rahmani et al. 2012). This is a clear indication that the found relationship has a high quality and can be used to represent the relationship between the considered variables (i.e. impact energy and moment of inertia).

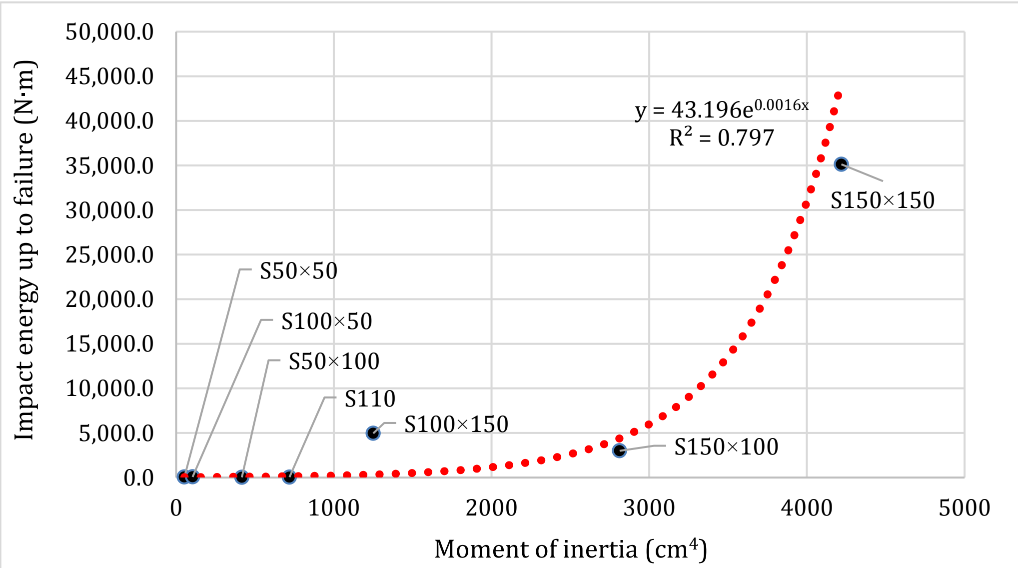


Fig. 7. Relationship between the moment of inertia and impact energy of concrete specimens.

On the other hand, the relationship between the impact energy and the cross-sectional area of the concrete beams was also evaluated. This relationship is presented in Fig. 8. The results showed that as the cross-sectional area of the beam increases, its impact performance increases. An exponential relationship between the cross-sectional area of the beam and the impact energy was found. This relationship has a value of R^2 close to 1. In general, as the cross-sectional area increases, the moment of inertia increases improving impact flexural strength of the beam, allowing it to absorb a higher impact energy.

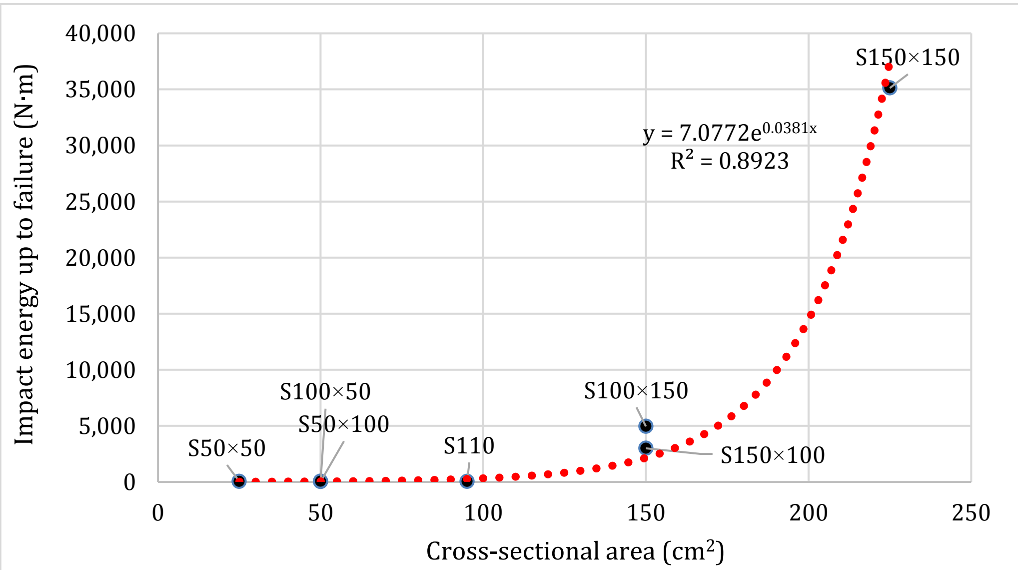


Fig. 8. Relationship between the cross-sectional area and impact energy of concrete specimens.

The results showed that the impact energy absorption capacity of concrete is a size dependent property that has a relationship with both the moment of inertia and the cross-sectional area of the test specimen. To evaluate the overall relationship between these three parameters, the relationship between the normalized impact energy and the normalized moment of inertia × the cross-sectional area (i.e., *I*×*A*) is graphically presented in Fig. 9. The normalized values were calculated taking the sample with the least cross-sectional area (i.e., S50×50) as the reference sample.

As can be seen from Fig. 9, there is a strong linear relationship with a value of R^2 = 0.88 between the normalized impact energy and normalized *I*×*A* of the concrete beams. This indicates that the impact performance of concrete greatly depends on both the moment of inertia and the cross-sectional area of the test specimen. These two properties are interconnected properties of the members. While the cross-sectional area depends on the dimensions of the cross-section, the moment of inertia depends on the dimensions and orientation of the cross-section.

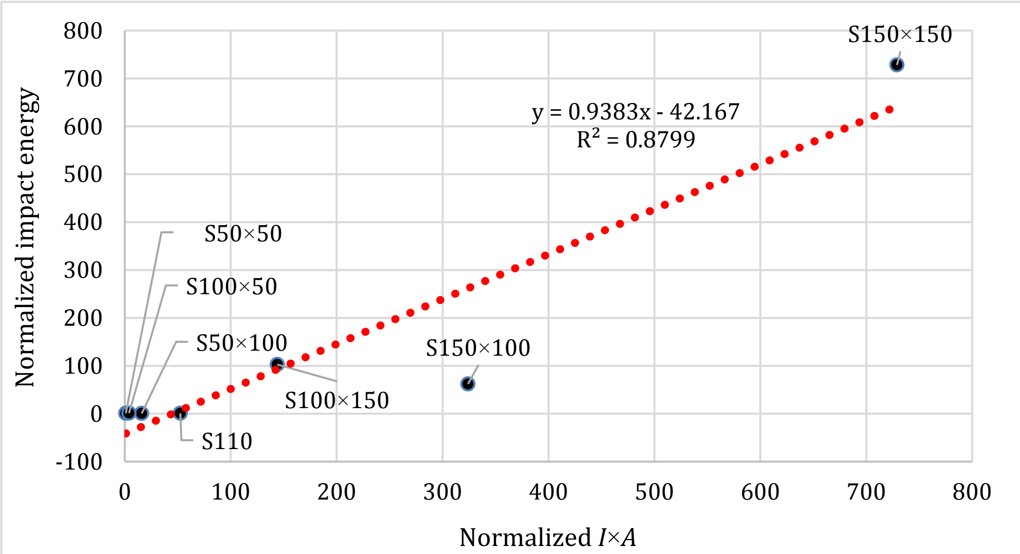


Fig. 9. Relationship between normalized cross-sectional area × moment of inertia (*I*×*A*) and normalized impact energy.

4. Conclusions

This research represents an experimental evaluation of the effect of the cross-sectional dimensions and orientation of concrete beams on their impact performance. Concrete beams with seven different cross-sectional dimensions and orientations have been tested under drop-weight test. A loading protocol for the repetitive impact test of samples having remarkably varying sizes has been proposed and validated. It was found that impact performance of concrete is a size dependent property. Increasing the moment of inertia and cross-sectional area of the concrete beams increased its impact performance. Increasing the moment of inertia of the sample increases its toughness and stiffness and accordingly its impact absorption capacity. Exponential relationships were found between the impact energy and both the moment of inertia and the cross-sectional area of the concrete beams. Moreover, a linear proportional relationship between the normalized impact energy and the normalized cross-sectional area × moment of inertia (*I*×*A*) was found. This indicates that the impact performance of concrete depends on both the cross-sectional area and the moment of inertia of the test beam (i.e., dimensions and orientation of the beam).

It is worth mentioning that while standards provide details on the dimensions of the standard samples that should be used in the evaluation of some mechanical properties under quasi-static loading, they generally don't provide much information regarding the standard dimensions of beam specimens under impact loading. Different cross-sectional dimensions and sizes have been used in the literature to evaluate the flexural impact performance of concrete. This indicates the necessity of more future research on this regard. This research provided some relationships between the cross-sectional dimensions and the impact performance of concrete. However, more research is still necessary. The size dependence of impact performance might depend on some other properties of concrete such as the compressive strength and the existence of additive materials. This hypothesis can be experimentally assessed in future research.

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Author Contributions
All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability
The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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