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Concrete impact strength as a measure of the resistance of a structure to external destructive energy

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Abstract

This paper presents authors' own tests of the impact strength of concrete. The impact tests were carried out using a pendulum ballistic hammer, two types of concrete with natural aggregate: with pebble (river) gravel aggregate and medium-grained crushed granite aggregate. The concretes were tested on cubic specimens with varying W/C ratios (0.40; 0.45; 0.50; 0.55). The surface roughness of the grains in the aggregates used for the concretes was measured using a profilometer. Concrete impact strength was determined by the energy absorbed by the specimen until failure. Concrete impact strength (E_A) was compared with compressive strength (f_c), tensile strength (f_{ct}) and stress intensity factor (K_{1c}).

Keywords: impact loads, concrete, roughness.

1 Introduction

Concrete is a widely used material in the construction of various buildings. Compressive and tensile strengths are commonly adopted measures of concrete strength. The procedure for determining the compressive and tensile strength of concrete is strictly described in standards (e.g. PN-EN-206.2014. Concrete, requirements, properties, production and conformity). The design and construction of concrete elements is usually concerned with the situation involving static loading, less often with dynamic loading. However, in practice, concrete elements can be loaded by exerting single or cyclic impacts. A few examples include: unintentional impact of a vehicle on a concrete column, pillar, bridge guardrail, etc. In special facilities, such as shelters, bunkers or special-purpose warehouses, there may be an impact on the concrete structure by means of explosives or projectiles of various calibers. In such situations, the impact of energy of different power is applied to the concrete structure, possibly resulting in its destruction or damage. The article attempts to clarify: whether the classical compressive or tensile strength of concrete determined by a static strength test is an adequate measure of the durability of an object or built-in element during a dynamic impact and the resulting destructive energy. Exemplary images of the destruction of concrete elements resulting from TNT and missile explosions are shown in Figures 1 and 2 (Dapeng Y. et al ,2021; Targut P.et al. 2013 Miakar P. F., et al 1998). The destruction of concrete elements presented in Figures 1 and 2 clearly indicate the effect of short-term impact load and destructive energy.

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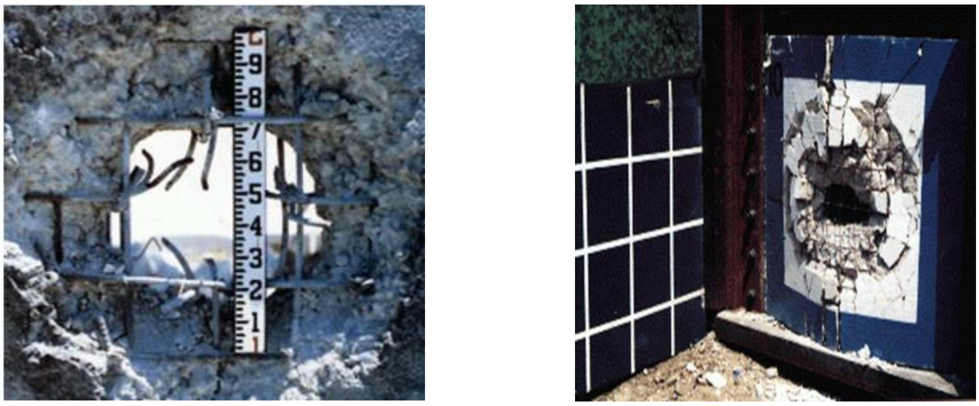


Figure 1. Investigation of concrete slab under the influence of explosion: a – view of a destruction plane of a plate in a special room, b – fragment of destruction.

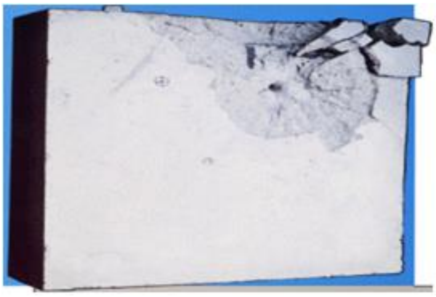


Figure 2. The range stand for testing of concrete slabs for puncture with a rifle bullet .

An analysis of the literature (Fic S., 2017, Zieliński A, 1981, Mahasneh B. Z. et al., 2015, Bookout L.A.,2012, Drathi R., 2015) has shown that during an impact on a concrete component, the delivered energy induces the propagation of a destructive stress wave in the material. These are complex waves of both tensile and, after a change of sign, compressive stresses. The energy itself, delivered to the element as a wave caused by the impact, can be absorbed by the material or reflected to varying degrees. The article presents a study of the impact strength of concrete, which was determined and compared with the compressive strength, tensile strength and stress intensity factor. The tested concrete was characterized by variable W/C, and pebble (river) aggregate and crushed granite aggregate were used as filler. In the literature one can find various designs of devices, which induce impacts on metal or concrete samples (Fic S., 2017, Zieliński A., 1981). These are usually hammers with a vertical falling striker, horizontal pneumatic hammers or pendulum hammers with a striker mounted on a rigid arm. To evaluate the impact strength of the material, the number of blows until the failure of the test specimen is given. From a practical point of view, the number of blows as a non-physical measure of a material resistance to impact is only an indicative indicator that is difficult to compare with other tests due to different testing devices, the height of lowering of the hammer striker with which the blows are exerted, or the size of the specimens used for testing (Zieliński A., 1981, Mahasneh B.Z., et al. 2015). The very design of the device exerting the impacts can cause interference, e.g., part of the impact load can be transmitted to the rigid arm connecting the hammer striker and the rest of the structure.

As shown in (Garbacz A., CourardL. , Kostana K., 2006, Łukowski P, 2016, Brandt A. M., 1974, Fic S, 2019), the strength of concrete depends, among other things, on the quality and physical-mechanical properties in the aggregate-cement slurry connection zone. This is related to irregularities on the surface of aggregate grains, i.e. surface roughness (Baldan, 2012, Garbacz A., Courard L., Kostana K., 2006, Brandt A. M., 1974, Fic S, 2012). The definition and terms related to surface roughness are included in PN-EN 4287 ISO (1999). The surface roughness of natural aggregate grains used in concrete is formed as a result of natural forces or by mechanical crushing of rocks. The research methodology and analysis of the surface roughness of aggregate grains used for concrete and the effect on impact strength are presented later in this article.

2 Author's own study

In order to test concrete for impact, a proprietary impact rig called a ballistic pendulum hammer was prepared (see Figure 3). The ballistic pendulum hammer consisted of a steel striker with a cylindrical tip with a base diameter of 2 cm, and an anvil with a shelf on which the concrete sample was placed. The anvil and the striker were suspended on steel cables (with bearings) about 3.2 m long to a fixed structure. The steel striker struck the concrete sample horizontally by opening an electromagnet. The swing of the anvil and the recoil of the striker at a single impact from the specimen were read on a scale. The strength of the concrete specimen was determined by the sum of the energy E_A [Nm], absorbed by the concrete specimen until its failure after N blows. The average energy per impact can be defined as: E_A/N. Standard 15x15x15 cm cube specimens were selected for compressive (f_c), tensile (f_{ct}) and impact (E_A) strength tests. In turn, 4x4x16cm beams were prepared for determining the stress intensity factor K_{1c} (according to RILEM recommendations). For concrete, washed pebble aggregate, i.e. river gravel and medium-grained crushed granite aggregate were used. The coarse aggregate fractions 4-8mm and 8-16mm, sand and CEM 35R Chelm cement were employed. The following W/C ratios were adopted: W/C= 0.40; W/C=0.45; W/C=0.50 and W/C= 0.55. Concrete strength (f_c), (f_{ct}), (K_{1c}), (E_A) was determined after 28 days of maturation of samples under standard conditions. Figure 4 shows an example of the failure of a concrete specimen on which impacts were exerted with a pendulum ballistic hammer. As a result of the exertion of impacts on the frontal plane of the sample, a characteristic imprint was formed, which, with successive impacts, formed a spreading cone destroying the sample. The destroyed concrete sample consisted of 4 prismatic parts with non-regular shapes. The magisterial lines of destruction in the concrete sample ran through the cement mortar and through the aggregate bond zone (Fig.4).

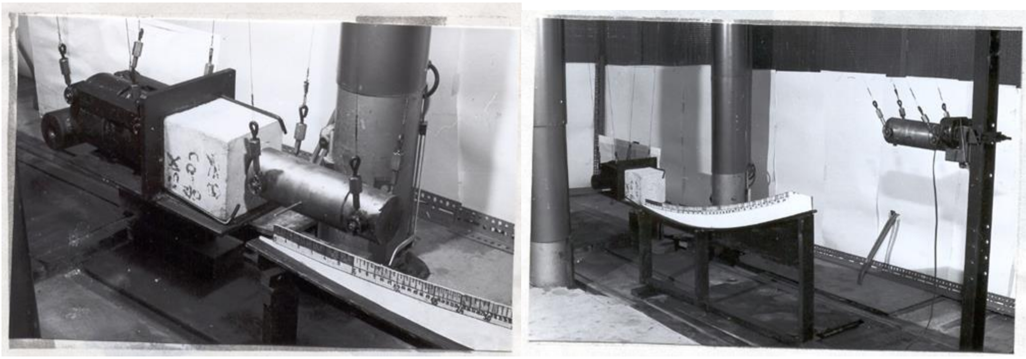
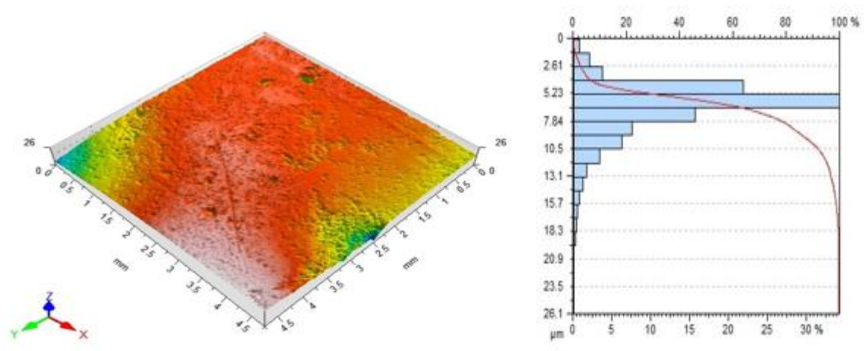


Figure 3. General view of the swinging ballistic hammer. View of the hammer and the anvil with the concrete sample placed in the front part.

Figure 4. Example of a concrete specimen damaged by impact.

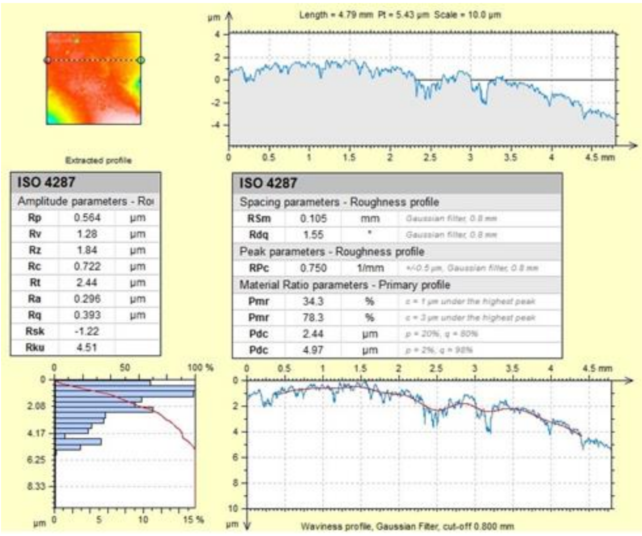
Surface roughness tests of gravel aggregate grains and granite were carried out using an Rc-120- 400 Hommel - Etamic profilometer with a 2 mm radius tip. The following parameters were measured: contour, surface roughness in 1D, 2D, 3D. The graphical form was obtained by automatic registration by the profilometer in contour or isometric form (axonometry), along with the necessary characteristics of elevations and depressions linearly R and on the plane S (the values of these parameters are shown in the tables in Figures 5, 6 and 7, 8). Roughness measurements were conducted on 5 samples of gravel and granite grains, respectively. The roughness measurements of gravel grains obtained from the tests are shown in Figures 5 and 7, whereas the results for granite grains are presented in Figures 8 and 9.

a) b) c)



ISO 25178		
Height Parameters		
Sq	2.59	µm
Sp	6.60	µm
Sv	19.5	µm
Sz	26.1	µm
Sa	1.85	µm
Functional Parameters		
Smr	0.387	%
EUR 15178N		
Amplitude Parameters		
St	26.1	µm
Sku	6.88	
Ssk	-1.52	

Figure 5. Surface characteristics of river pebble gravel grains; (a) 3D surface; (b) histogram and Abbott-Fireston curves; (c) measured parameters on the surface S.



ISO 4287		
Amplitude parameters - Ro		
Rp	0.564	µm
Rv	1.28	µm
Rz	1.84	µm
Rc	0.722	µm
Rt	2.44	µm
Ra	0.296	µm
Rq	0.393	µm
Rsk	-1.22	
Rku	4.51	

ISO 4287			
Spacing parameters - Roughness profile			
RSm	0.105	mm	Gaussian filter, 0.8 mm
Rdq	1.55	°	Gaussian filter, 0.8 mm
Peak parameters - Roughness profile			
RPc	0.750	1/mm	+/-0.5 µm, Gaussian filter, 0.8 mm
Material Ratio parameters - Primary profile			
Pmr	34.3	%	c = 1 µm under the highest peak
Pmr	78.3	%	c = 3 µm under the highest peak
Pdc	2.44	µm	p = 20%, q = 80%
Pdc	4.97	µm	p = 2%, q = 98%

Figure 6. Grain roughness characteristics of river pebble gravel along length L, in 2D.

a) b) c)

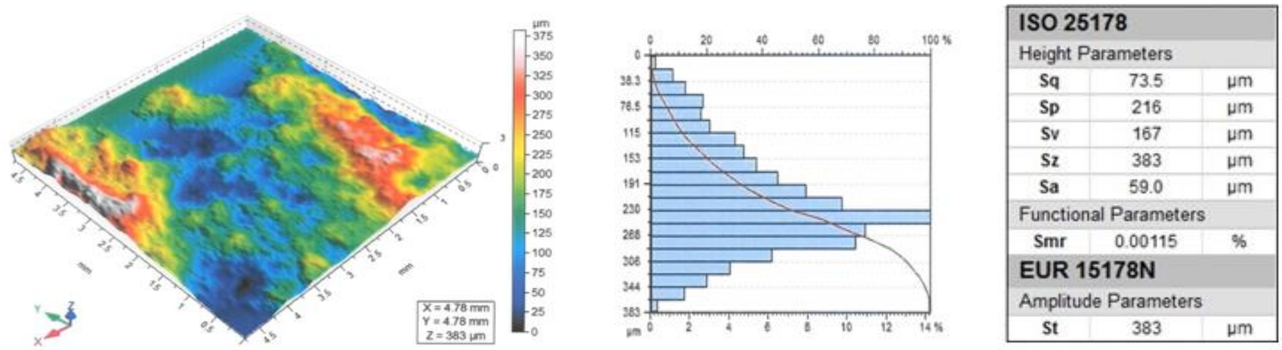


Figure 7. Surface characteristics of medium-grained granite; (a) surface in 3D; (b) histogram and Abbott-Fireston curves; (c) measured parameters on the S-surface.

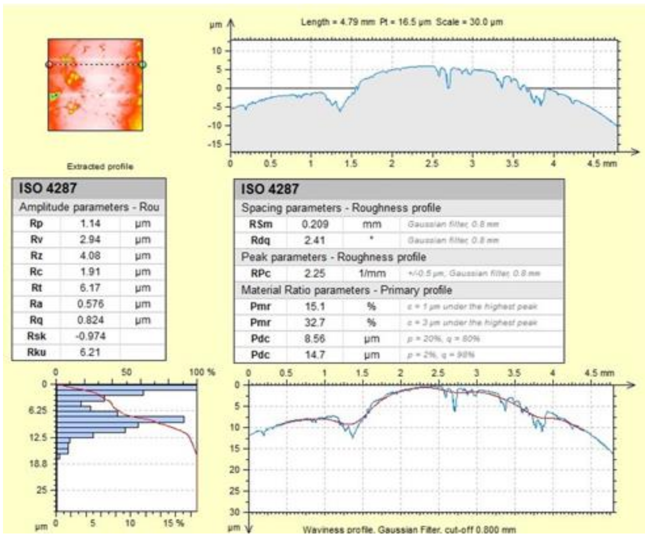


Figure 8. Characteristics of granite grain roughness along length L, in 2D.

Table 1. Summary of compressive strength (fc), tensile strength (fct), stress intensity factor (K1c) and impact strength (EA) determined on samples after 28 days of hardening under standard conditions, BZ – concrete with gravel aggregate, BG – concrete with granite aggregate.

Series	**f_c**	**f_{ct}**	**E_A**	**K_{1c}**
	[MPa]	[MPa]	[Nm]	[MN/m$^{3/2}$]
BZ 0.40	49.16	4.18	2115	1.193
BZ 0.45	43.86	4.01	1615	0.989
BZ 0.50	38.12	3.81	949	0.917
BZ 0.55	33.20	2.94	739	0.851
BG 0.40	59.43	5.16	2715	1.595
BG 0.45	54.94	4.79	1981	1.412
BG 0.50	50.30	4.21	1678	1.201
BG 0.55	41.20	3.52	1015	0.877

3 Analysis of research results

Measurements of the surface roughness of pebble aggregate grains – river gravel and crushed granite aggregate showed clear differences in surface texture. The flakiness planes formed when granite rock was mechanically crushed ran through the weakest areas of crystallized minerals. Granite grains after crushing had a crepe-like shape, with a developed plane caused by numerous indentations and protuberances as shown in Figure 7 (e.g., in 3D). From the study of the roughness of the aggregates used for concrete, it can be seen that the developed plane of the surface of the granite aggregate grains was about 2.1 times larger compared to the gravel aggregate grains. Histograms and Abbott-Fireston curves show these differences: gravel R_A 0.284; granite R_A 0.596 (Figures 5 and 7). The damage image of the concrete specimens showed that wedging of the cement slurry was formed in the depressions on the surface of the granite aggregate grains, thereby increasing the adhesion surface compared to the smooth surface of the pebble aggregate grains. The wedging of the cement slurry in the recesses of the granite grains increased the strength parameters of the tested concretes compared to those with pebble aggregate. Prokopski G.W and Halbiniak J. (2000) pointed out that adhesion of cement slurry to rough grains is better, which is due to higher cohesion (adhesion) forces in the ITZ bond zone. Moreover, they reported that the aggregates with a smooth surface (river gravel in this study) already propagate cracks at lower stresses compared to the concretes with crushed aggregates. Figures 9 and 10 show the characteristic failure crack in both gravel and granite aggregate concretes after impact exertion. In the concretes with gravel aggregate, the failure crack was through the ITZ and cement matrix, while in the concretes with granite it was through the joint in the hills and matrix. Sheared fragments of cement slurry remained in the surface depressions of the granite (Figure 10, detail A). The propagation of the shock wave in the form of applied energy caused tensile and compressive stresses in the concrete composite. In the cement matrix, the shock wave propagated more slowly compared to the aggregate grains. This is due to the different properties of the two materials used to make the concrete ($p1v1 < p2\ v2$, where p1, p2- the density of the matrix and aggregate, and the difference in elastic modulus $E1 < E2$ about 3 times). The rapidly propagating wave in the concrete, after passing through the cement matrix, encounters the ITZ as an interface with the aggregate grains, and stresses are concentrated. As the ITZ is a weak spot in the structure of concrete, the so-called wall effect (Neville A.M., 2008, Larrard de F.,

1999) there is an overstressing of the joint and the formation of a failure crack and its development up to the failure of the material (Zieliński A, 1981, Brandt A.M, 1974). When concrete is loaded statically, there is a phenomenon of stress redistribution and relieving weak areas in the material (Larrard de F., 1999).

Table 1 shows the strength parameters of the two concretes tested. Meanwhile, the graphs (Figures 11 and 12) show the percentage change in the strength of the concretes when the W/C ratio is increased. Increasing the W/C ratio, for example, from 0.4 to 0.5 of gravel concrete resulted in a 55% decrease in E_A, 33% decrease in f_c, 23% decrease in K_{1c}; in turn, in the case of the concrete with granite aggregate the reductions were as follows: E_A by 32%, f_c by 15%, f_{ct} by 19% and K_{1c} by 25%. In the graphs presented in Figures 11 and 12, it is clear that increasing the W/C ratio had the greatest effect on the value of E_A compared to K_{1c}, f_c, and f_{tc}. This means that the change in the basic parameter characterizing concrete, which is the W/C ratio, determines the demonstration of a faster deterioration process in concrete as a result of external energy delivered during the exertion of impacts compared to tests under static loading. At the same time, as shown by the performed tests, the roughness of the grain surface in favor of granite compared to the smooth grain surfaces of pebble gravel has a significant impact on all strength parameters.

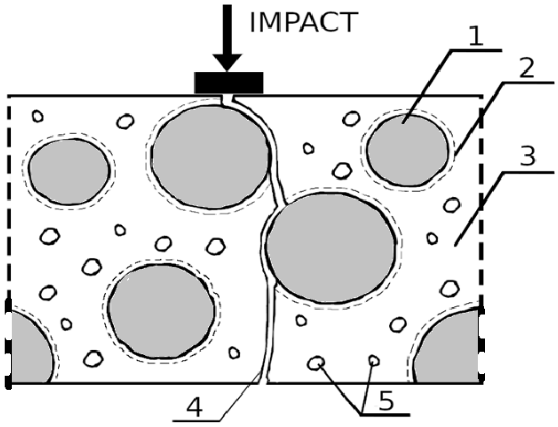


Figure 9. The course of the failure line in a concrete specimen of pebble aggregate concrete caused by impacts. 1. pebble aggregate grain, 2. Interface Transition Zone, 3. cement matrix, 4. the course of the failure crack, 5. pores and capillaries in the cement matrix.

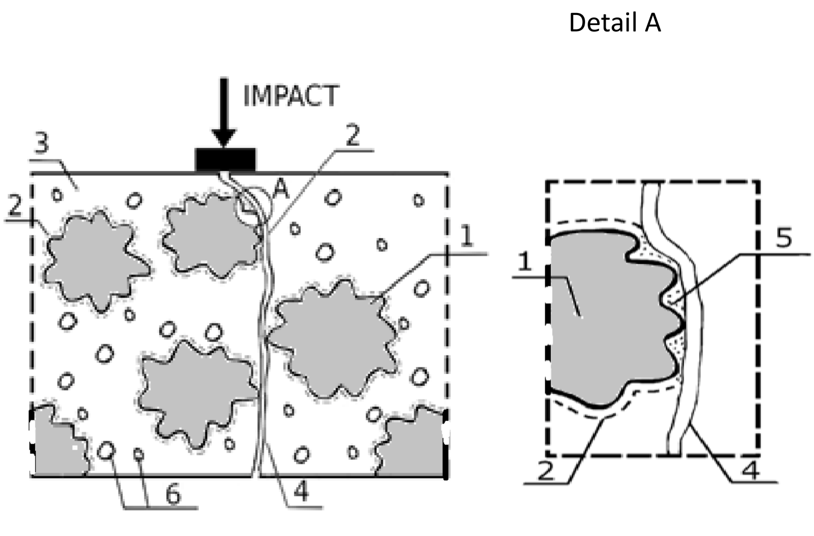


Figure 10. The course of the failure line in concrete with granite aggregate, caused by impacts. 1. granite grain, 2. Interface Transition Zone, 3. cement matrix, 4. the course of the failure crack, 5. pores and capillaries in the cement matrix.

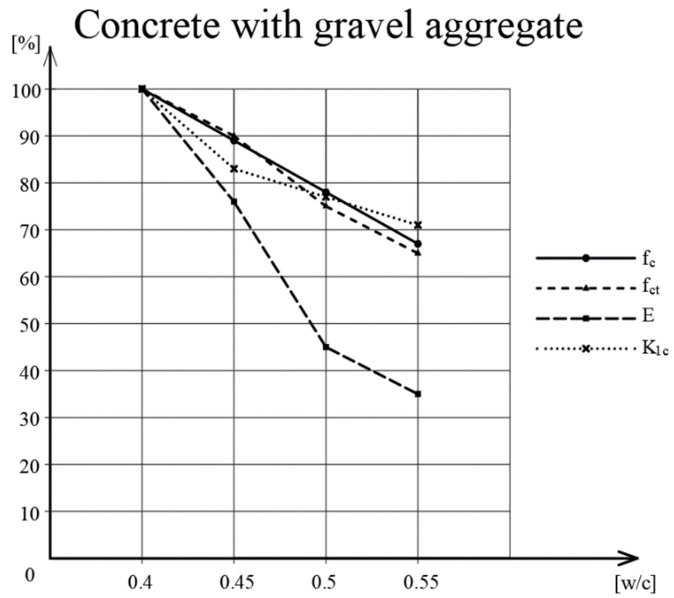


Figure 11. Percentage decrease in compressive strength fc, tensile strength fct, total destructive energy produced by impact E_A and stress intensity factor K_{1c} determined on concrete specimens with pebble aggregate at varying W/C.

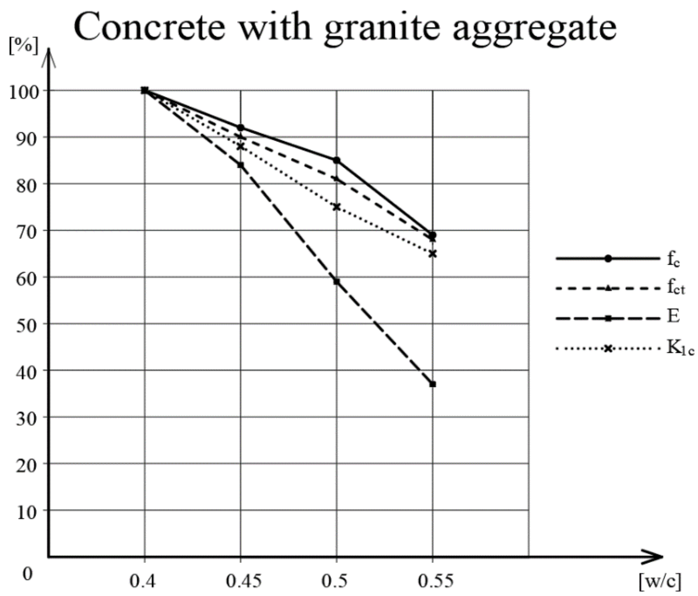


Figure 12. Percentage decrease in compressive strength fc, tensile strength fct, total destructive energy produced by impact E_A and stress intensity factor K_{1c} determined on concrete specimens with crushed granite aggregate under varying W/C.

Testing concrete by impacts enables to accurately record the changes created in the structure of the material with a change in the W/C ratio and the variation in the roughness of the aggregate grain surface. The applied impact load and the resulting energy appear to be closer to the actual conditions created by the action of applying an explosive to concrete compared to the traditional testing of this material under static loading, i.e. determining the compressive or tensile strength. It can also be noted that concretes with a higher W/C ratio absorb a greater amount of energy in single impacts cushioning the impact and energy accumulation (lesser swing of the hammer's striker) resulting in faster material failure.

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