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Determination of the impact resistance of concrete as experimental and numerical

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ABSTRACT

This study investigated the change of impact resistance in concrete with respect to their sample size and compressive strength as experimental and theoretical. In the experimental design phase, a three-parameter, four-level L16 (43) Taguchi orthogonal array was used. For the Charpy impact tests, 16 serial samples were prepared with the following characteristics: sample width/sample length (B/L) ratio of 0.20, 0.25, 0.40 and 0.50; a sample width (B) of 100, 150, 200 and 250 mm, and a relative notch length (a/B) of 0.1, 0.2, 0.3 and 0.4. Experimental data were analyzed by two different methods. In the first stage, the optimum values were determined by performing analyses with the Taguchi method, while in the second stage, a mathematical model created by the Response Surface Method (RSM) was used as the objective function in a genetic algorithm to obtain the optimum values. Validation tests were performed based on optimum values and the results were compared. As a result of the study, it was observed that the change in sample size and compressive strength significantly affected the impact resistance of the concrete. A mathematical model was created to determine the impact resistance of the concrete.

Keywords: Concrete; Impact resistance; Charpy impact testing; Taguchi Method; Response Surface Method.

1. INTRODUCTION

In general, many structures are exposed to short-term dynamic effects. Therefore, a structure must be protected not only against static loads but also against dynamic effects [1]. The effects of dynamic loads on the structure are different to static loads. Dynamic loads disrupt the structural integrity by causing instantaneous energy accumulation in the structure and it can result in significant damages or even destructions. In recent years, due to the dramatic increase in terrorist incidents and to climate change, it is increasingly necessary for structural calculations, to take into account the effects of hurricanes and explosions in addition to static loads [2]. Dynamic loads occur as a result of impacts such as earthquakes, hurricanes, explosions, ships or waves colliding with bridge piers and vibration of machinery in factories. The effects of impacts have a more complex structure than tensile strength or bending stress. The need to accurately estimate the behaviour and resistance of structures under impact loads has led to research into the determination of the mechanical properties of materials and structural elements against impact effects [1].

There are different standardized methods for determining the impact resistance (I_s) of materials. For metal and plastic materials, Charpy and Izod impact tests can be performed according to the principles specified in ASTM and ISO standards to determine their impact resistance [3–6]. For concrete, on the other hand, the drop weight method based on the principles given in the ACI 544 standard is widely used [7]. While fracture energy and impact resistance are determined quantitatively in Charpy and Izod methods, the drop weight method uses the number of weight drops as the basis for determining when the first crack occurs in the concrete sample, and then the number of cracks increases such that the sample loses its bearing capacity [8]. Recently, studies have been concentrated on the applicability of the Charpy method to directly determine the energy required to fracture concrete as a result of an impact [9–12]. On the other hand, since there is no standard for determining the impact resistance of mortars and concretes using the Charpy method, it is not possible to make comparisons between studies in published literature. The most important reason for this is that the sizes of test samples are too small and they do not represent the concrete structure, and thus samples in different sizes are used in each study.

While experimentally investigating the properties of concretes, it takes 28 days to prepare samples for testing. When the number and level of test parameters are increased, various problems arise, like the increase in the number of samples, longer test times and greater difficulty in interpreting the test results. To eliminate these

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disadvantages, the use of statistical or numerical methods during the experimental design phase and analysis of the obtained data provides great advantages.

One of the experimental design and analysis methods is the Taguchi Method. The Taguchi Method, a statistical method that takes into account the effects of parameters on the result, was developed by Genichi Taguchi in the 1950s as an optimization process technique. When the analysis is performed using this method, reliable results can be obtained since the effects on the result of known factors as well as unknown factors are taken into consideration. In this method, optimum values for both parameter levels and test results can be achieved with fewer experiments by using the Taguchi orthogonal array in the experimental design stage. It saves the researchers time and material because the optimum value can be determined with fewer experiments [13].

When optimization is performed in the Taguchi Method, optimum values are found according to parameter levels. However, the optimum values can also be the intermediate values of the parameter levels. In this case, optimization by methods such as Genetic Algorithms is useful in reaching the final result.

Genetic Algorithms (GA) introduced in the 1970s by Holland are an adaptive optimization search algorithm inspired by Charles Darwin's theory of natural evolution. Genetic Algorithms have gained increasing popularity in solving optimization problems by finding the optimal solution without a specific initial condition. The Genetic Algorithm method is applied randomly on an initial population which is a population or subpopulations of chromosomes used, and where later, all the individual chromosomes are appraised by a suitability function. In the evaluation phase, this suitability function takes into account the quality of the solution. In this method, crossover and alteration functions are considered as the main operators that randomly affect the suitability value. Chromosomes are selected for reproduction by assessing their suitability value. Selection, crossover, mutation and elitism are applied to the initial population to achieve a better resolution in each generation. When optimum values are reached in the suitability function, the process is terminated [14–17].

When the existing literature studies on determining the impact resistance of concrete with Charpy impact testing were examined, each researcher carried out his/her experiments on samples of a specific size. However, the effect of sample size and concrete strength on the determination of the impact resistance of concrete by Charpy notch impact testing was not investigated. This study will make an important contribution to the literature by determining the impact resistance of concretes based on their size and strength using Charpy notch impact testing with the help of a mathematical model. It will also provide an insight into establishing a standard to determine the impact resistance of concrete with Charpy notch impact testing.

2. MATERIALS AND METHODS

In the concrete mixture calculation, aggregates with a maximum diameter of 16 mm and specific gravity of 2.62 kg/dm^3 were used. The sieve analysis of the aggregate was performed in accordance with TS 706 [18]. The sieve analysis values of these aggregate are presented in Table 1.

The properties of CEM I 42.5 N type Portland cement complying with TS EN 197-1 standard [19] used in mixtures are given in Table 2. Concrete mixing ratios prepared in accordance with TS 802 [20] are given in Table 3.

Table 1: Properties of aggregate.

SIEVE SIZE (mm)	CUMULATIVE PASSING (%)
16	100
8	73
4	57
2	45
1	37
0.50	24
0.25	19
0.15	9
0.063	4
Pan	0

Table 2: Properties of the cement.

CHEMICAL PROPERTIES		PHYSICAL PROPERTIES	
S (SiO_2)	21.12	Specific gravity (g/cm^3)	3.13
A (Al_2O_3)	5.62	Blaine fineness (cm^2/g)	3370
F (Fe_2O_3)	3.24	Initial setting time (min)	168
C (CaO)	62.94	Final setting time (min)	258
MgO	2.73	Compressive strength (MPa)	
SO_3	2.30	2. day	25.8
Na_2O	–	7. day	41.8
K_2O	–	28. day	50.7
Cl	0.009		
Loss of ignition	1.78		

Table 3: Concrete mixing ratios for 1 m^3 (kg).

CEMENT	WATER	AGGREGATE SIZE (mm)			
		0–2	2–4	4–8	8–16
429	193	605	196	232	614

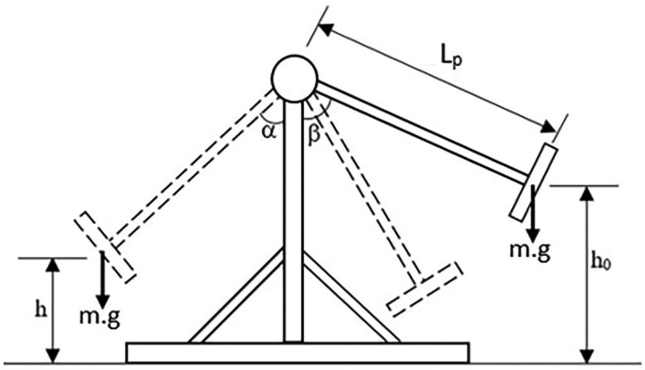

Figure 1: Charpy Impact Apparatus.

The Charpy impact test developed by Georges Charpy measures the energy required to break a notched sample with an impact load. Although widely used for metals, it can also be applied to ceramics, composite materials and polymers [21]. In the Charpy impact apparatus illustrated schematically in Figure 1, the difference between the energy of the pendulum before the impact and the energy after the specimen breaks is measured and the energy required to fracture the sample can then be found.

The Charpy impact test is used to determine material toughness by hitting a test specimen with a hammer, mounted at the end of a pendulum. The specimen is broken by a single blow from a pendulum that strikes the middle of the specimen on the un-notched side. The different between the height pendulum is dropped from, and the height it rises to after impact, gives the amount of energy absorption involved in deforming and breaking the specimen [22]. Standard Test Methods for Notched Bar Impact Testing of Metallic Materials were used to calculate the energy required for the concrete sample to be fractured. Additionally, Equation 1 was also used [4]:

$$E_f = m \cdot g \cdot (h_0 - h) = m \cdot g \cdot L_p \cdot (Cos\alpha - Cos\beta) \quad (1)$$

In Eq. 1 the symbols have the following meaning:

E_f: Amount of energy required to break the sample (Joule)
m: Mass of the pendulum hammer (kg)

g: Gravitational acceleration (m/s^2)

h_0: Initial drop height of the pendulum hammer (m)

h: The final height of the pendulum hammer after the fracture (m)

L_p: Pendulum length (m)

β: Initial drop angle of pendulum (degree)

α: Final angle of the pendulum after fracture (degree)

The Charpy notch impact test is used to determine the amount of energy absorbed by the material as a result of impact to determine the toughness of metals. The metal sample sizes used in the experiment are very small compared to the concrete sample sizes. For this reason, the Charpy experimental setup was modified according to the concrete sample sizes used, as shown in Figure 2.

In all samples prepared according to Figure 3, the sample thickness (D) was fixed at 50 mm. The other dimension of the impact test specimens such as sample support interval (L), sample width (B) and relative notch lengths (a/B) are given in Table 4. In addition, for each experimental series, 150 mm cubic samples were prepared for compressive strength tests.

The impact resistances (I_s) were calculated by dividing the fracture energy of each series into the useful cross-sectional areas. For that purpose, Equation 2 was used. Normalized impact resistance (q_c) values, which reflect the concrete impact resistance and pressure strength ratio were used in the analyses because concrete samples of different strengths were prepared, and these values were found using Equation 3.

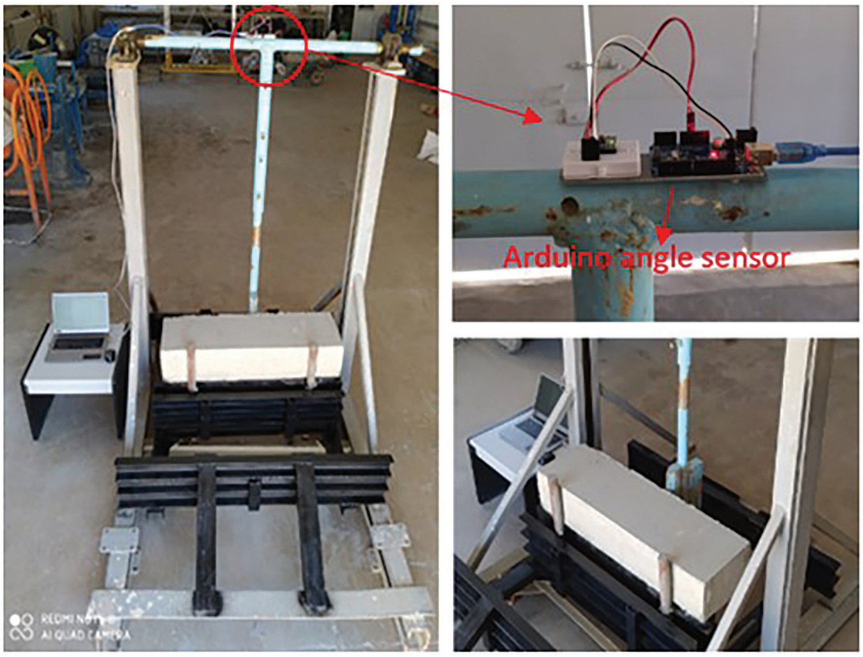

Figure 2: Modified Charpy test setup.

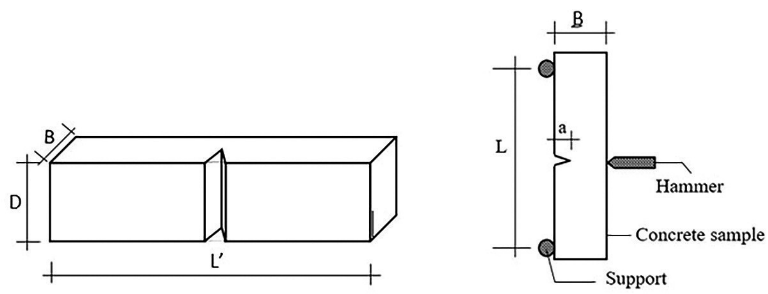

Figure 3: Charpy impact test sample shape.

Table 4: Levels of the control factors used for experiments.

PARAMETERS		LEVELS			
		LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
A	Sample width/Sample length, B/L	0.20	0.25	0.40	0.50
B	Sample width, B (mm)	100	150	200	250
C	Relative notch length, a/B	0.1	0.2	0.3	0.4

$$I_s = E_f/(D \cdot (B - a)) \tag{2}$$

$$q_c = I_S/\sqrt{f_c} \tag{3}$$

The Taguchi Method is used for optimizing the process of experimentation in an effort to improve robustness, design productivity and enhance product quality. The main idea of the Taguchi Method is to improve the quality without changing the parameters that affect the result. The design approach of the Taguchi Method offers a systematic and efficient method not just in terms of design engineering but also in terms of cost and performance in many areas [23].

The Taguchi Method uses orthogonal arrays to determine the effect of a large number of variables on the result with a small number of experimental data. Thanks to the orthogonal array, all the data necessary is obtained from the full factorial of the parameters and the results that depend on them [24]. The Taguchi Method has been applied in many fields of engineering including civil engineering [25–28].

Standard Taguchi orthogonal arrays are used to evaluate the effects of each experimental parameter on the result. A loss function value is defined to calculate the deviations between the analysis result and the desired value, and this value is transferred to a signal-to-noise (S/N) ratio. The S/N ratio also minimizes the effects of unknown parameters on the result. In general, there are three types of S/N ratios depending on the characteristics of the desired result. Calculations of these S/N ratios are given in Equations 4 to 6 respectively [29–30]. L16 Taguchi orthogonal array is given in Table 5.

Table 5: L16 Taguchi orthogonal array.

SERIAL NUMBER	A	B	C	B/L	B	a/B	SAMPLE SIZES (mm)		
							B	L	a
S1	1	1	1	0.20	100	0.1	100	500	10
S2	1	2	2	0.20	150	0.2	150	750	30
S3	1	3	3	0.20	200	0.3	200	1000	60
S4	1	4	4	0.20	250	0.4	250	1250	100
S5	2	1	2	0.25	100	0.2	100	400	20
S6	2	2	1	0.25	150	0.1	150	600	15
S7	2	3	4	0.25	200	0.4	200	800	80
S8	2	4	3	0.25	250	0.3	250	1000	75
S9	3	1	3	0.40	100	0.3	100	250	30
S10	3	2	4	0.40	150	0.4	150	375	60
S11	3	3	1	0.40	200	0.1	200	500	20
S12	3	4	2	0.40	250	0.2	250	625	50
S13	4	1	4	0.50	100	0.4	100	200	40
S14	4	2	3	0.50	150	0.3	150	300	45
S15	4	3	2	0.50	200	0.2	200	400	40
S16	4	4	1	0.50	250	0.1	250	500	25

*** The sample thickness (D) was fixed at 50 mm.

1. Lower is better (LB), chosen when the goal is to minimize the response. The S/N can be calculated using Equation (4):

$$^{S}/_{N} = -10 * \log_{10}\left(\frac{1}{n}\sum_{i=1,}^{n} Y_i^2\right) \tag{4}$$

2. Higher is better (HB), chosen when the goal is to maximize the response. The S/N is calculated using Equation (5):

$$^{S}/_{N} = -10 * \log_{10}\left(\frac{1}{n}\sum_{i=1,}^{n} \frac{1}{Y_i^2}\right) \tag{5}$$

3. Nominal is better (NB), chosen when the goal is to target the response and it is required to base the S/N on standard deviations only. The S/N is calculated using Equation (6):

$$^{S}/_{N} = -10 * \log_{10}\left(\frac{1}{n}\sum_{i=1,}^{n} (Y_i - Y_0)^2\right) \tag{6}$$

Response Surface Method (RSM), used in modeling and analysis of experimental data in different engineering fields, is a method that combines mathematical and statistical techniques. Its fundamental principle is to use experimental variables to obtain the response model. The degree of this model usually ranges from one to four, but the higher the degree of a nonlinear model, the more difficult it is to simulate. Therefore, the quadratic polynomial given in Equation 7 is preferred, which has higher calculation accuracy and solving efficiency [31–33].

$$y = a_0 + \sum_{i=1}^{k} a_i X_i + \sum_{i=1}^{k} a_{ii} X_i^2 + \sum_{i<j}^{k} a_{ij} X_i X_j + \varepsilon \tag{7}$$

In Eq. 7 the symbols have the following meaning:

y: Response (objective function)

a_o, a_i, a_{ii}, a_{ij}: Polynomial coefficients

X_i, X_j: Experimental variebles

k: The number of experimental variables

ε: The fitting error

The Genetic Algorithm technique is used to solve complex engineering optimization problems. John Holland first introduced the idea of Genetic Algorithms (GA) in 1975. Genetic algorithms are used in many engineering [34–35].

GA is a search procedure based on both natural genetics and natural selection mechanics, and has many advantages;

- Generally, it does not use gradient information in the search process. GA methodologies are therefore direct search procedures that enable them to be applied to a wide range of optimization problems.
- GA procedure uses more than one solution per iteration, unlike most classical optimization algorithms that update one solution per iteration.
- GA procedure uses stochastic operators as opposed to the deterministic operators used in most classical optimization methods. Operators tend to achieve the desired effect by using higher possibilities for the desired results, rather than using predetermined and fixed transition rules [36].

When optimizing with a Genetic Algorithm, variable parameters such as Genetic Algorithm population, chromosome length, crossover probability and mutation probability should be defined, otherwise the correct result may not be obtained [37].

3. RESULTS AND DISCUSSION

In this study, sample beams and cubes were prepared for each series. After the samples were cured for 28 days, the Charpy impact test was performed on the notched beam samples and compressive strength tests were performed on the cube samples. Fracture energy (E_f), Impact resistance (I_s) and compressive strength (f_c) test results are given in Table 6.

Normalized impact resistance (q_c) values were calculated with Equation 3 by using the impact resistance and compressive strength values of the concrete given in Table 6. In the Taguchi Method, these values were placed in the L16 orthogonal array and S/N ratios given in Table 7 for each series were calculated using Equation 5.

The values in Table 7 were analyzed using the Taguchi Method and optimum values were determined. The analysis results are shown in Figure 4.

Based on the analysis results of the Taguchi method, the optimum values were determined as shown in Figure 4. As can be seen from Equation 3, where the normalized impact resistance (q_c) is calculated, the q_c value and impact resistance varied with respect to each other. Therefore, parameter levels with a large q_c value (B/L = 0.50, B = 100 mm and an a/B = 0.40) were taken as the optimum values.

In order to conduct optimization by using experimental data with a Genetic Algorithm, an objective function was created and this function is given in Equation 8. The Response Surface Method (RSM) was used to create the objective function.

$$q_c = \frac{I_s}{\sqrt{f_c}} = -0.840 + 13.959 * B/L - 0.010 * B - 0.808 * a/B - 0.010 * B/L * B + 3.024 * B/L * a/B - 12.827 * {B/L}^2 + 2.450 * {a/B}^2 \quad (8)$$

In order to determine the reliability and statistical significance of the objective function, the variance analysis of (ANOVA) given in Table 8 was performed.

As a result of the variance analysis, the p-value of the model was found to be less than 0.0001. This value indicates that the model is reliable. When the F values were examined, the variance analysis result showed that the most effective parameter was B/L (F = 4670.13), and the most ineffective parameter was B · a/B (F = 10.42).

After the Model was created, it was optimized by genetic algorithm. In the optimization process, limitations were set according to the requirements. These values are given in Table 9.

Table 6: Experimental results.

SERIAL NUMBER	f_c (MPa)	E_f (N · mm)	I_S (N · mm/mm^2)
S1	28.41	14009.42	3.11
S2	28.41	15047.30	2.51
S3	28.41	21295.43	3.04
S4	28.41	32954.95	4.39
S5	32.27	23548.27	5.89
S6	32.27	29738.14	4.41
S7	32.27	36291.85	6.05
S8	32.27	51667.67	5.90
S9	30.15	38228.24	10.92
S10	30.15	47499.04	10.56
S11	30.15	63840.60	7.09
S12	30.15	79005.18	7.90
S13	33.06	42660.34	14.22
S14	33.06	55310.91	10.54
S15	33.06	70792.52	8.85
S16	33.06	88878.24	7.90

Table 7: Normalized values (q_c) and S/N ratios of the experimental series.

SERIAL NUMBER	B/L	B	a/B	q_c	S/N
S1	0.20	100	0.1	0.583	–4.687
S2	0.20	150	0.2	0.471	–6.540
S3	0.20	200	0.3	0.570	–4.882
S4	0.20	250	0.4	0.824	–1.682
S5	0.25	100	0.2	1.037	0.316
S6	0.25	150	0.1	0.776	–2.203
S7	0.25	200	0.4	1.065	0.547
S8	0.25	250	0.3	1.039	0.332
S9	0.40	100	0.3	1.989	5.973
S10	0.40	150	0.4	1.923	5.680
S11	0.40	200	0.1	1.291	2.219
S12	0.40	250	0.2	1.439	3.161
S13	0.50	100	0.4	2.473	7.864
S14	0.50	150	0.3	1.833	5.263
S15	0.50	200	0.2	1.539	3.745
S16	0.50	250	0.1	1.374	2.760

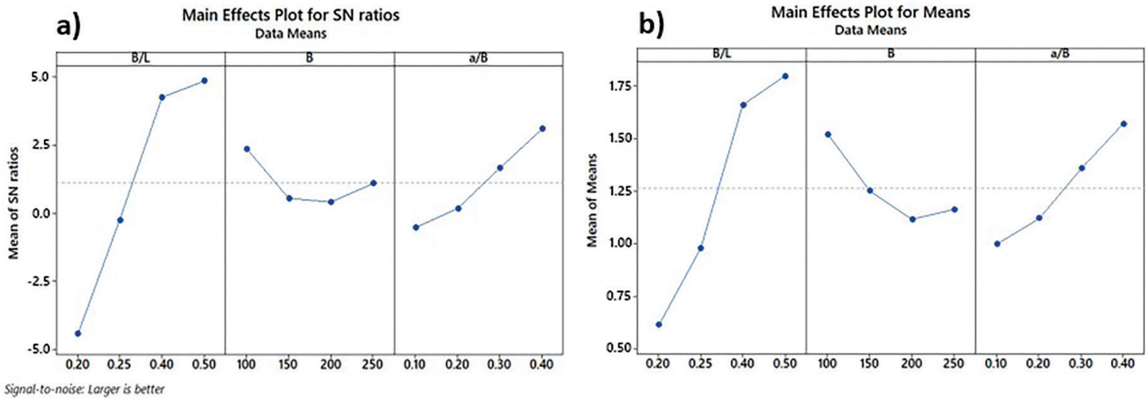

Figure 4: Analysis results of the Taguchi Method.

Table 8: Analysis of variance (ANOVA) of the model.

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F – VALUE	P – VALUE
Model	5.01	8	0.6259	820.56	<0.0001
B/L	3.56	1	3.56	4670.13	<0.0001
B	0.0543	1	0.0543	71.16	<0.0001
a/B	0.1288	1	0.1288	168.85	<0.0001
B/L.B	0.0224	1	0.0224	29.35	0.0010
B · a/B	0.0080	1	0.0080	10.42	0.0145
$(B/L)^2$	0.1920	1	0.1920	251.74	<0.0001
B^2	0.1040	1	0.1040	136.36	<0.0001
$(a/B)^2$	0.0096	1	0.0096	12.59	0.0094
Residual	0.0053	7	0.0008		
Total	5.01	15			

Table 9: The limit values of the Genetic Algorithm parameters.

Population Size	100
Number of Generation	500
Cross over Probability	0.90
Mutation Probability	0.01

Equations 2, 3 and 8 were used to derive Equations 9 and 10, where the impact resistance (I_s) of concrete and the amount of energy required to fracture the sample (E_f) was calculated.

$$I_s = \Big(-0.840 + 13.959 * B/L - 0.010 * B - 0.808 * a/B - 0.010 * B/L * B + 3.024 * B/L * a/B - 12.827 * {B/L}^2 + 2.450 * {a/B}^2\Big) * \sqrt{f_c} \tag{9}$$

$$E_f = I_s * (D * (B - a)) \tag{10}$$

The optimum values obtained from the analyses and confirmation test results at these values are given in Table 10. As can be seen from Table 10, there is more than a 95% similarity between the experimental results and the optimization results. These values are an indication of the reliability of the optimization done with both methods.

To observe the change of impact resistance (I_s) according to test parameters (B/L, B and a/B), the three-dimensional graphs given in Figure 5 were prepared.

Table 10: Optimization and confirmation test results.

		TAGUCHI METHOD	GENETIC ALGORITHM	CONFIRMATION TEST
Experimental Parameters	B/L	0.50	0.50	0.50
	B	100	100	100
	a/B	0.40	0.40	0.40
Normalized Impact resistance (q_c)		2.554	2.456	2.473
Impact Resistance (I_s) (N.mm/mm^2)		14.68	14.12	14.22
Fracture Energy (E) (N.mm)		44040	42360	42660

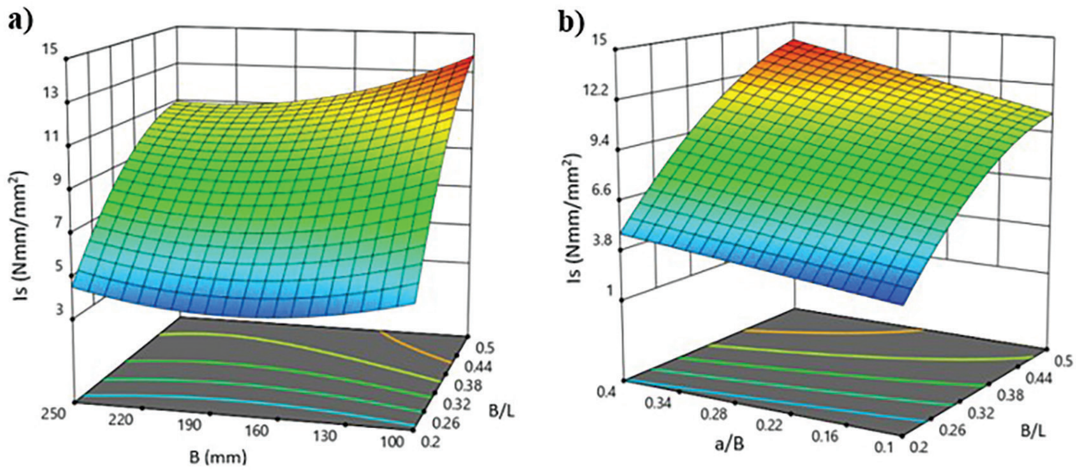

Figure 5: Change of impact resistance with respect to test parameters.

Table 11: Analysis of variance for I_s.

CONTROL FACTORS	DEGREES OF FREEDOM	SUM OF SQUARES	VARIANCE	F	CONTRIBUTION OF FACTOR (%)
B/L	3	247.70	81.34	223.48	81.61
B	3	10.54	3.58	8.55	4.35
a/B	3	30.71	10.24	27.49	10.13
Error	6	3.24	1.97		3.91
Total		292.19			100

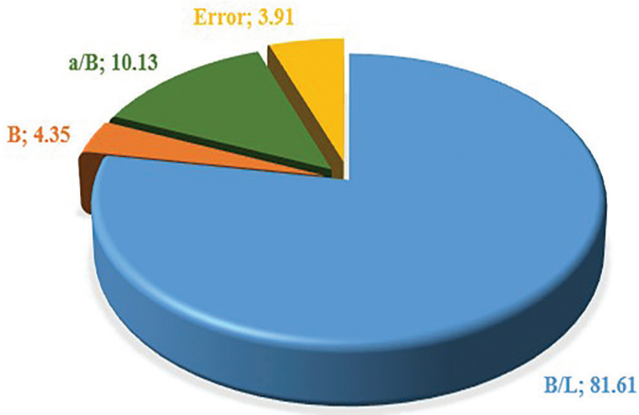

Figure 6: The effect ratios of the experimental parameters on Impact resistance (%).

When Figure 5 is examined, it is seen that the change in the B/L ratio had an effect on the impact resistance. As this ratio increased, the width of the sample increased and its length decreased; thus, more energy was required to fracture it.

As can be seen from Figure 5, as the ratio between the notch length (a) and sample width (a/B) increased, the impact resistance also increased. Although the cross-sectional area decreased as a result of increased notch length, the impact resistance increased.

Analysis of variance, also called ANOVA, is one-step in the process of identifying and explaining the reasons for different outcomes. In experimental studies, variance analysis is an appropriate statistical method to determine the effects of variables on the response. Minitab software was used for the analysis of variance given in Table 11. In addition, the error rate and the effect of experimental parameters on the response are shown in Figure 6.

As can be seen from Table 11 and Figure 6, B/L (77.43%) is the most effective factor, the second most important factor is the value of a/B (10.13%). Both of them are more significant than B (4.35%). Although B/L is the most effective factor, an increase in L decreased the impact resistance. In contrast to B/L, the increases in values of B and a/B increased the impact resistance, too.

4. CONCLUSIONS AND EVALUATION

The results obtained in this study to determine the impact resistance of concrete using the Charpy notch impact test, which is not yet a test standard, are given below:

- The energy and impact resistance required to fracture the concrete due to impact can be determined using a modified Charpy notch impact test setup.
- To determine the impact resistance of concrete, an equation (Eq. 9) was developed based on sample sizes and strength.
- Optimum values were obtained at the parameter level with statistical methods such as the Taguchi method. However, it would be more appropriate to use numerical methods and a genetic algorithm to find optimum values other than the parameter level. It was seen in this study that test and analysis results were reliable.

To standardize the determination of the impact resistance of concrete by Charpy notch impact testing, it is necessary to investigate the effects of different parameters. Thus, the following points can be considered in future studies:

- The results can be compared by applying different impact energies to concrete samples.
- The results can be interpreted by preparing notched and un-notched test samples.
- The variation of the impact resistance can be investigated not just to the compressive strength, but also according to the flexural tensile and splitting tensile strengths.

The conclusions should be concise and represent the most important aspects found during the reported work development. They should seek to point out the scientific and/or technological and/or theoretical progress effectively achieved.

5. ACKNOWLEDGMENTS

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