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Experimental Research of Impact Toughness of the Kazakhstani Construction Steel—Assessment of Compliance with the Provisions of 1993 Eurocode

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Abstract

Since 2015, the Republic of Kazakhstan has a new regulatory framework for construction on the basis of Eurocode. Many new steel quality requirements have been introduced for steel structures. As a result, Kazakhstan's steel production almost ceased to be used in construction. Therefore, a series of studies is being carried out to determine the quality of local steel for compliance with the requirements of Eurocode 1993. Impact toughness testing was carried out on 126 samples of 8, 10, 20 mm thick structural steel produced by the "Arcelor-Mittal" company. The experimental study of impact toughness of KCV and KCU at a temperature of +20˚, −20˚, −40˚ degrees were conducted for seven types of structural steel, the most common in the Republic of Kazakhstan, on the experimental experimentation facility of the KazRDICA JSC. The ST RK STB EN 10045-1-2012 techniques were used. In each series of tests, 3 specimens were used. It has been established that in all cases the temperature requirements of Eurocode 1993 (National Annex to SP RK EN1993-1-1: 2005/2011*, Table НП.2*) are met. A regression relationship between the values of impact toughness and temperature was constructed. It has been established that construction steel produced in the Republic of Kazakhstan fully complies with the requirements of 1993 Eurocode. The studies on the dependence of Brinell hardness of steel on the impact toughness of steel at specified temperatures are performed. The correlation dependencies between the values of impact toughness and BH Brinell hardness have been obtained.

Keywords

Impact Toughness, Steel Hardness, Construction Steel, Eurocode, Brittle Fracture

1. Introduction

A new regulatory framework in construction based on the Eurocode has been in force in the Republic of Kazakhstan since 2015. However, due to insufficient knowledge of stress-related properties and compliance with Eurocode requirements, steel constructions are used in insufficient quantities.

It is noted in the literature sources that the impact toughness testing appeared in practice much earlier than the corresponding theory was developed [1]. The first notched-bar tests were carried out at the end of the 19th century. In 1901, Charpy built his first pendulum hammer and developed a methodology that, with slight variations, is still used today. As a result of notched-bar test, the expended mechanical energy is determined, which is equal to the work produced, which is then applied to the effective cross-sectional area of the specimen. Consequently, the units of impact toughness are J/cm^2 [2].

The concept of impact toughness has proved so impactful that research on testing of this kind continues to the present day [3] [4] [5] [6]. For example, in [3] the effect of shock pulse during dynamic compact tension tests with the help of instrument-controlled pendulous impact machine is investigated. The light shock tests were performed on Charpy specimens made of $42CrMo_4$ cast steel and EN-GJS-400-18 spheroidal graphite cast iron with different crack geometries at several impact velocities. Inertia effects occurring on the specimens and components of the pendulum impact testing machine were identified using laser displacement and velocity measurements. The dynamic compact tension tests have shown incomplete energy conversion because some of the applied energy is absorbed by the components of the pendulum impact testing machine. This may result in increased stress on the sample.

The impact test technique was used to conduct impact test on 9 specimens to study the impact resistance of high-strength steel beams with round holes in the lintel blocks [7]. The experimental results have demonstrated that the change of impact energy significantly affects the dynamic response and damageability of the beam.

The impact testing machine was used to perform impact testing on 15 specimens to study the impact resistance of high strength steel beams (HS) with hexagonal holes in the lintels [8]. The empirical equations for the relationship between impact energy, steel strength and dynamic characteristics have been established.

In recent years, the high-tensile-strength steel has been widely used in the construction of large-span and high-rise structures as it can improve the mechanical performance of building structures and reduce their dead weight. In this study, a side impact test using a jackhammer was performed on 22 high-strength circular steel (CHS) pipes with axial preloading. The test parameters included impact energy, pipe diameter to thickness ratio, axial compression ratio, and hammerhead shape. Data on fracture modes and the entire impact process, including the impact strength, displacement, deformation, and axial force history of the specimens have been obtained [9].

Therefore, impact toughness tests or impact force is very meaningful for understanding the structures response in the condition close to the limit state.

According to the principal provisions of the Eurocode 1993, constructional steel structural steel must have sufficient impact toughness to exclude brittle failure of tensile members at the lowest operating temperature within the design life of the structure. According to the National Annex to SP RK EN1993-1-1: 2005/2011* the values of KCU (KC is a symbol of impact strength, the third symbol shows the type of notch: sharp (V), with a radius of rounding (U) impact strength vary between 29 - 34 J/cm^2. For C345K (S275) steel alone, the KCU is 39 J/cm^2.

We continue the study cycle on the topical issue of verification of the requirement of compliance of Kazakhstani steel characteristics with Eurocode 1993 [9]. Previously such a task has not been solved in the Republic of Kazakhstan. Therefore, it is necessary to check the compliance of local constructional steel with the specified requirements for impact toughness values.

Previously, the problem of determining the hardness of Kazakhstan steel has been solved [10].

2. Materials and Methods

The experimental studies were carried out with the help of a pendulum hammer ИО50030-0.3. The impact-testing machine was calibrated in February 2023—certificate is available. The freezing of the samples was performed using an LGT 2325 freezer. The certificate of certification of testing equipment is available.

For seven types of constructional steel most common in the Republic of Kazakhstan, experimental research of impact toughness of KCV and KCU at temperatures of +20˚, −20˚, −40˚ degrees was carried out at the experimental facilities of JSC "Kazakh Scientific Research and Design Institute of Civil Engineering and Architecture". The methods of ST RK STB EN 10045-1-2012 have been applied. Three specimens were used in each test runs. A total of 126 steel samples with thickness of 8 - 20 mm (Kazakhstani-made St3Sp5, 09G2S). **Figure 1** shows the test specimens, **Figure 2** shows the pendulum hammer ИО50030-0,3 certified for testing according to ISO standards. **Figure 3** demonstrates constructional steel specimens after impact toughness tests.

3. Results

Table 1 contains the average values (sample mean) of impact toughness at different temperatures.

Table 2 summarizes the values of probability characteristics of impact toughness obtained from the data of **Table 1**.

The analysis of **Table 2** shows that in all cases of temperature control the requirements of Eurocode 1993 are met (National Annex to SP RK EN1993-1-1: 2005/2011*, Table NP.2*).

Figure 1. Construction steel specimens prepared for impact toughness testing.

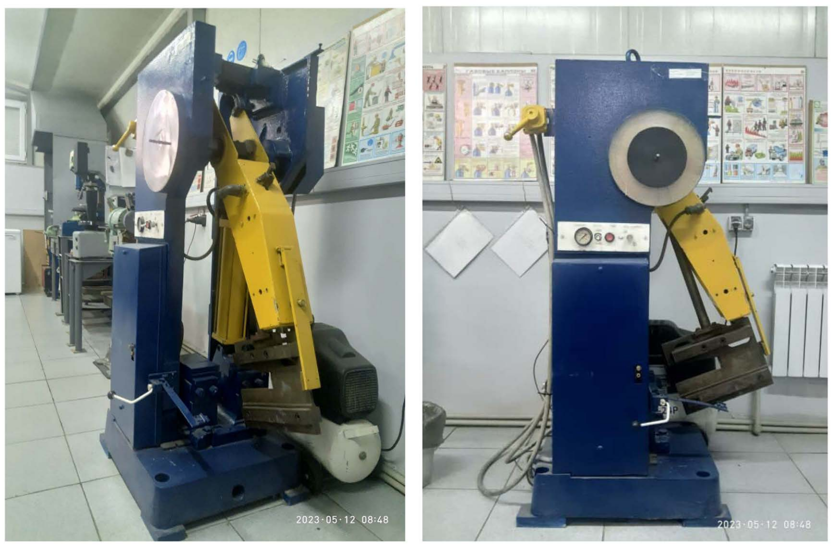

Figure 2. Impact machine for the impact toughness testing.

Figure 3. Construction steel specimens after impact toughness testing.

Table 1. Impact toughness values at different temperature, J/cm^2.

N°	KCU, +20°	KCU, −20°	KCU, −40°	KCV, +20°	KCV, −20°	KCV, −40°
1	147	70	61	128	58	51
2	157	91	66	152	67	49
3	121	71	57	100	59	47
4	142	76	62	112	58	47
5	166	79	59	125	68	49
6	174	86	71	133	66	54
7	167	85	65	181	72	53

Table 2. Probabilistic characteristics of impact toughness value at different temperature, J/cm^2.

N°	KCU, +20°	KCU, −20°	KCU, −40°	KCV, +20°	KCV, −20°	KCV, −40°
Sample mean	153	80	63	133	64	50
Standard deviation	18.3	8.0	4.7	26.7	5.6	2.8
Variation coefficient	0.12	0.1	0.08	0.2	0.09	0.06
Median value	157	79	62	128	66	49

$$\text{KCU} \geq 29\ \text{J/cm}^2 \text{ or } 34\ \text{J/cm}^2, \quad (1)$$

$$\text{KCU} \geq 34\ \text{J/cm}^2. \quad (2)$$

The sample mean and median values do not differ by more than 3%, which allows to conclude that the normal distribution of impact toughness as a random variable is acceptable. The variation coefficient is rather small, which makes it possible to speak about the stability of the probabilistic characteristics of impact toughness.

Each batch of constructional steel is accompanied by a certificate of conformity issued by the manufacturing plant, which contains the physical and mechanical characteristics of the batch of steel plates. Table 3 shows the average values of impact toughness at different temperature. The analysis of the certificates shows that the results of impact toughness tests are given, where the series have from 3 to 6 values. Then the average value over the series is calculated by the relevant formulas. Only in 1 case the average value of the impact toughness value was given at once.

It should be noted that the impact strength values declared on the certificates of conformity also fully comply with the requirements of Eurocode 1993 (1)-(2).

The values of the sample mean from Table 2 can be conveniently approximated by a linear regression relationship. Using MathCAD PRIME package the following relations are obtained

Table 3. Impact toughness values at different temperature according to certificates of conformity, J/cm^2.

N°	KCU, +20°	KCU, −20°	KCU, −40°	KCV, +20°	KCV, −20°	KCV, −40°
1		78		147		
2		67		181		
3			123			
4			92			
5	-	57		77		
6	-	-	97	-	-	-
7	-	153	-	216	-	-

$$\text{KCU}(T) = 119.286 + 1.546T^0 \text{, correlation coefficient 0.988,} \quad (3)$$

$$\text{KCV}(T) = 101.429 + 1.432T^0 \text{, correlation coefficient 0.985.} \quad (4)$$

where T^0—temperature in degrees.

Figure 4 and Figure 5 show the indicated dependencies and experimental points. The spread of impact toughness values is generally insignificant.

Previously, 7 types of structural steel manufactured in Kazakhstan were tested for BH Brinell hardness [10]. The numbering of column from Table 1 corresponds to the numbering of the first row from Table 4.

Figures 6-11 (Table 5) summarizes the experimental data between average Brinell hardness values and average impact toughness values. There linear approximations are presented as

$$\text{BH} = A\text{KCU} + B \quad \text{or} \quad \text{BH} = A\text{KCV} + B \quad (5)$$

A, B—approximating coefficients.

Table 5 demonstrates the values of A and B coefficients for each of the 6 cases of dependence between the values of impact toughness and hardness, as well as the value of the linear correlation coefficient.

For example, linear dependences for the temperature −20 for values of KCU and KCV impact toughness will be as follows

$$\text{BH} = -0.87\text{KCU} + 223.39, \quad (6)$$

$$\text{BH} = -2.13\text{KCV} + 290.08. \quad (7)$$

It should be noted that the magnitude of correlation coefficients is quite high for KCU values at +20 degrees Celsius and KCV values at −40 degrees Celsius. For the other cases, the spread in values is quite high. Subsequently, the nonlinear regression dependence can be constructed.

The hardness value is a universal strength property of structural steel—it is possible to determine steel yield strength, tensile strength and relative elongation at break using correlation dependencies [11] [12].

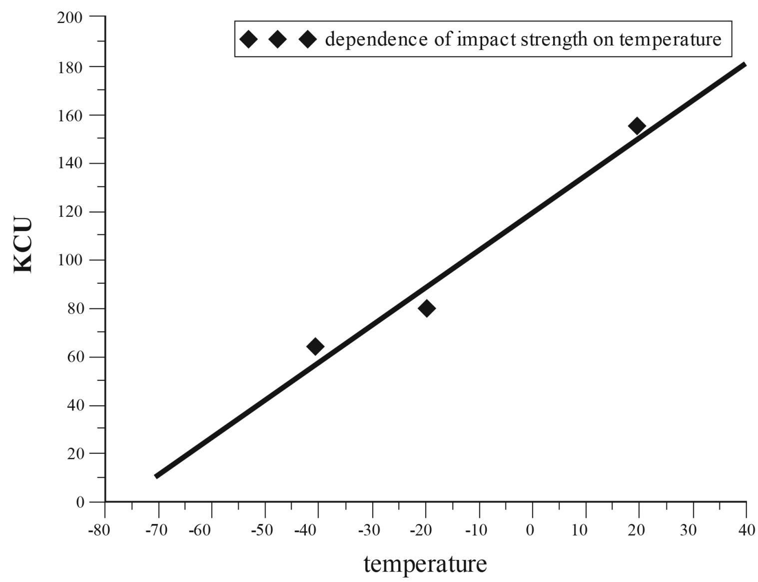

Figure 4. Experimental points and approximating dependence for the values of KCU impact toughness.

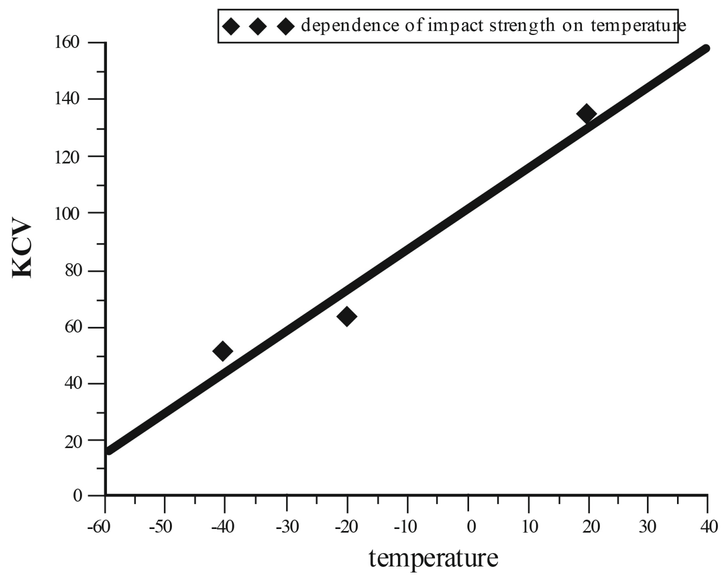

Figure 5. Experimental points and approximating dependence for KCV impact value.

Table 4. Brinell hardness test.

Test number	Steel 1	Steel 2	Steel 3	Steel 4	Steel 5	Steel 6	Steel 7
1	133	151	174	182	128	144	155
2	139	154	184	176	125	143	151
3	142	150	175	173	124	146	144
4	139	155	183	174	125	141	149
5	137	154	189	180	122	149	147
Mean value	138	153	191	177	125	145	149

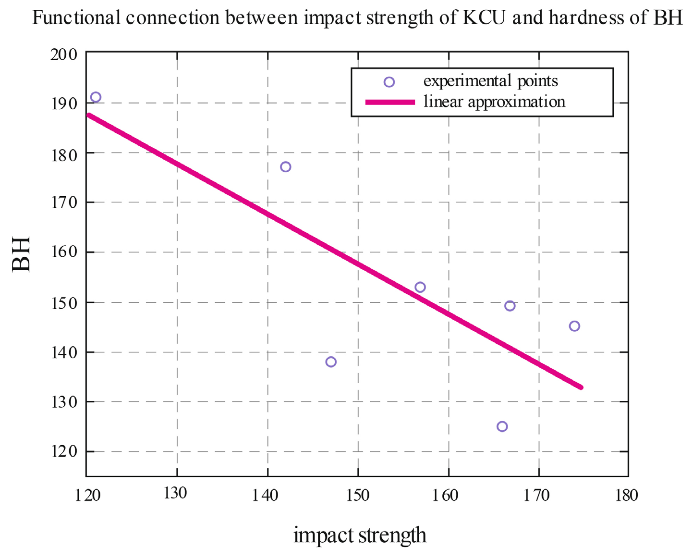

Figure 6. Relationship between KCU impact toughness and BH Brinell hardness at temperature +20.

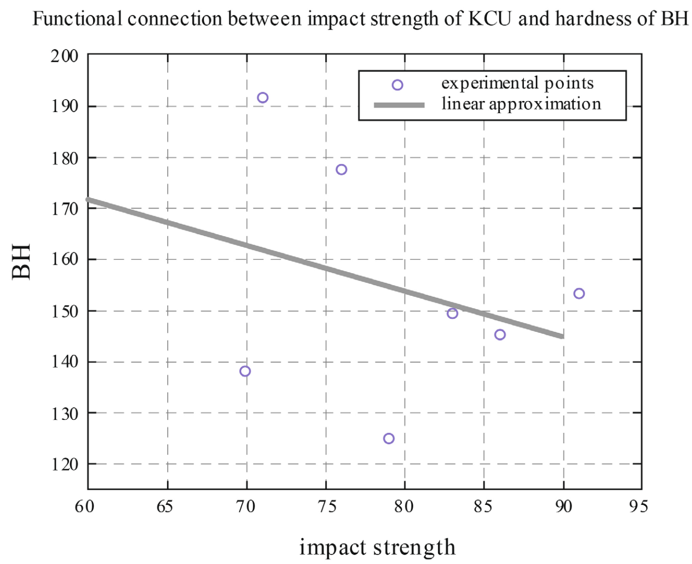

Figure 7. Relationship between KCU impact toughness and BH Brinell hardness at temperature −20.

Table 5. Approximating coefficients of linear dependence.

N˚	A	B	Correlation coefficient
1	−0.99	305.84	−0.795
2	−0.87	223.39	−0.300
3	−1.36	239.57	−0.282
4	−0.39	205.26	−0.453
5	−2.13	290.08	−0.526
6	−4.77	401.45	−0.808

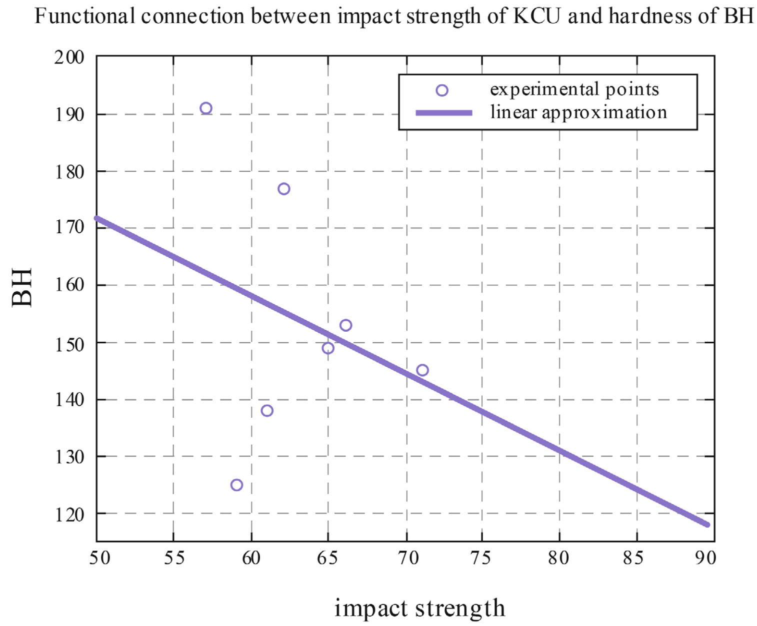

Figure 8. Relationship between KCU impact toughness and BH Brinell hardness at temperature −40.

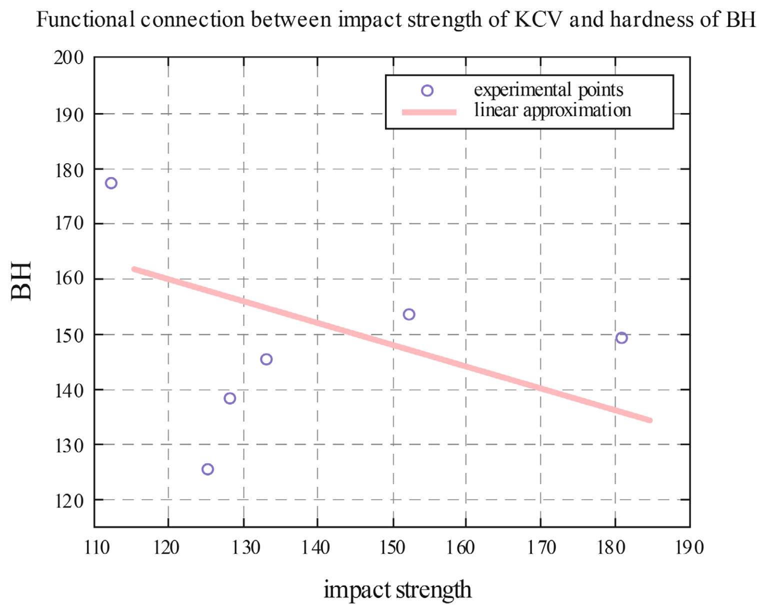

Figure 9. Relationship between KCV impact toughness and BH Brinell hardness at temperature +20.

4. Discussion

It is known that according to the requirements of Eurocode 1993, in order to avoid brittle fracture, structural steel must have sufficient impact strength at the lowest operating temperature within the design service life of the structure. In the northern and central regions of the Republic of Kazakhstan, the operating temperature varies from +40 to −40.

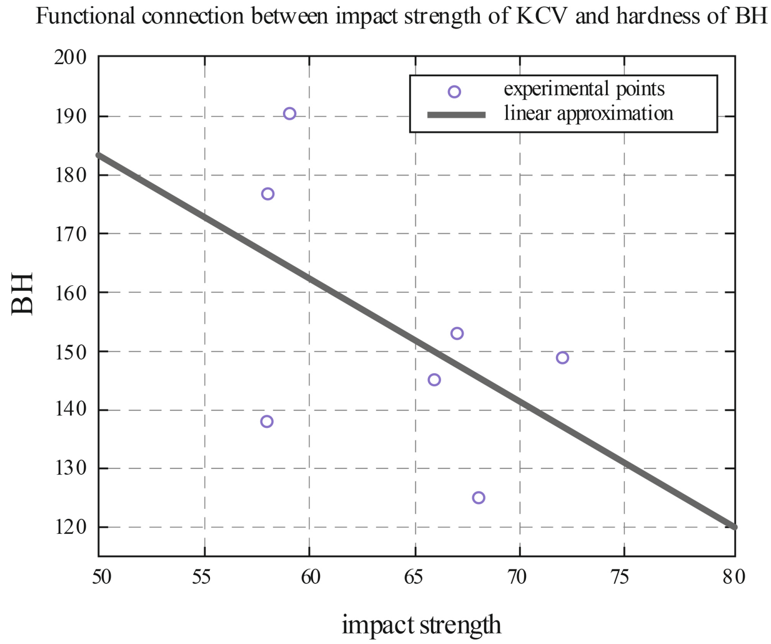

Figure 10. Relationship between KCV impact toughness and BH Brinell hardness at temperature −20.

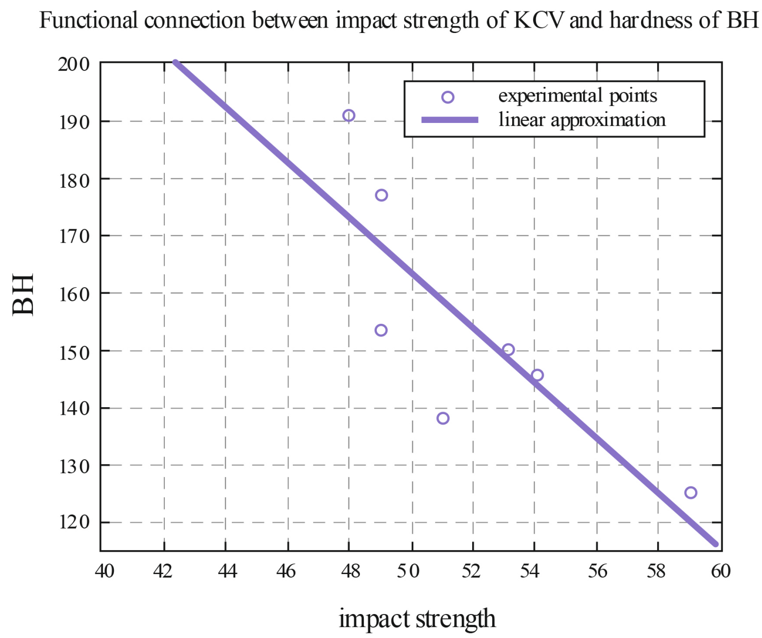

Figure 11. Relationship between KCV impact toughness and BH Brinell hardness at temperature −40.

In 2015, a new regulatory framework based on the Eurocode was adopted in Kazakhstan. As a result, the construction of steel frame buildings using local steel (Arcelor Mittal, Karaganda) practically ceased in the Republic of Kazakhstan. The structural steel used was imported from Europe, which greatly increased the cost of construction.

An important result of this work is objective results on compliance Kazakhstan structural steel requirements for impact strength, available in Eurocode 1993. This opens up the possibility of widespread use of local steel for construction in ordinary and seismic hazardous areas. This reduces the cost of construction and this is especially true for seismic areas. In the city of Almaty, the use of steel frame buildings, where seismicity is 9 - 10 points and there are numerous tectonic faults [13].

Therefore, the results of the work are of great importance for seismic construction in the Republic of Kazakhstan.

Another important result is the establishment of correlations between the Brinell hardness of the structural bond and the toughness values at different temperatures (Formulas (5), (6), (7), **Table 5**). The hardness values can be used to determine the toughness values. This is relevant for the tasks of examining building with a steel frame. It is possible to determine the Brinell hardness values very quickly and not expensive. Therefore, the given formulas have an important application value.

In addition, the possibility of using Kazakhstan's structural steel in construction will be useful for potential investors.

5. Conclusions

1) For the first time, experimental studies on determination of impact toughness values of the most common samples of local structural steel have been conducted in the Republic of Kazakhstan.

2) For 8 - 20 mm thick structural steel specimens (St3Sp5, 09G2S) the requirements of the Eurocode 1993 by impact toughness values are met (National Annex to SP RK EN1993-1-1: 2005/2011*, Table НП.2*).

3) The impact strength values declared on the certificates of conformity also fully comply with the requirements of Eurocode 1993 (1) and (2).

4) The regressional relationships (3) and (4) may be used to interpolate impact strength values at intermediate temperatures as well as for extrapolation at temperature values outside the range specified in **Table 1**.

5) The regressional relationships allow determining the BH Brinell hardness values from the values of impact toughness. Following that, by correlation dependences it is possible to determine the values of yield strength, tensile strength and relative elongation at break.

6) The basic results of the work allow using Kazakhstan structural steel for design and construction of steel structures in the northern regions of Kazakhstan, where winter temperatures can be below −40 degrees Celsius, and in southern regions where the summer temperatures exceed +40 degrees Celsius.

7) The results of the article will contribute to the use of Kazakhstani structural steel in seismically hazardous areas, for example, in the East Kazakhstan region of the Republic of Kazakhstan. This area is characterized by a seismic hazard of 7 - 9 points and low winter temperatures.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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