

Effect of the Size Factor on Leeb Hardness Performance in Pyroclastic Rocks

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Abstract

The aim of the study is to research the effect of sample size on the Leeb hardness (HL) test, commonly used as an indirect, non-destructive, cost-effective and practical method to predict the uniaxial compressive strength of rocks. Within this scope, cube samples were prepared with 3, 4, 5, 6, 7, 8, 9 and 10 cm edges from 10 different pyroclastic rocks with physical features (density, porosity, P-wave velocity) varying over a broad interval. After identifying the physical (dry density, porosity and P-wave velocity), mineralogical and textural features of each sample, the HL test was applied under laboratory conditions to investigate the effect of the size factor. Correlation analysis between HL values and sample size revealed that samples with cube edge lengths below 8 cm exhibited markedly lower HL values, accompanied by substantially higher standard deviations. An 8 cm cube edge length was identified as the minimum reliable sample edge length for HL measurements of pyroclastic rocks. HL testing is not recommended for rocks containing components with contrasting surface hardness values. The findings are expected to contribute to the application of Leeb hardness, with expanding areas of use in recent years, in more effective and reliable ways in engineering projects.

Keywords

Leeb hardness (HL), size factor, minimum reliable sample edge length, pyroclastic rock

1 Introduction

Leeb hardness (HL), which has begun to be used commonly for rocks in recent years, is a non-destructive method developed by Swiss engineer Dietmar Leeb in 1975 to determine the surface hardness of metals and polymers [1]. Use of the HL test has become more popular in different disciplines (civil engineering, architecture, geomorphology, restoration work, rock mechanics, etc.) due to its mobility, large measurement interval, small surface of the probe of the device and opportunity to determine impact direction [1–8]. Previous researchers examined the correlations between this test and physical and mechanical features [1, 9–22]. In these studies, the area receiving most focus was prediction of uniaxial compressional strength. For prediction of this value, researchers used approaches like simple regression, multiple regression, artificial neural network and fuzzy [1, 9–16, 23, 24]. High correlation relationships were obtained for the prediction models developed in these studies. Studies in recent times stated that the HL test was affected by the pore [25–27], grain or crystal size [1, 8, 28–30] on the surface of the samples. Some researchers defined the optimum sample

size required with the aim of removing the effect of sample size (cube or core) on the HL values [1, 9, 13, 14, 17, 27, 31–33]. Verwaal and Mulder [9] observed that diameters below 50 mm provided low results for HL measurements in core samples. İnce and Bozdağ [1] stated that cube samples prepared from magmatic rocks should have edge lengths of at least 7 cm. The study by Kolgitti and Çelik [32] found HL measurement results displayed variability linked to volume of the core sample and stated that for consistent results, sample volumes should be above 215 cm³. Ghorbani et al. [27] tested block and core samples in both diameter and axial directions. They proposed minimum length/diameter (L/D) ratio and volume sample values of 1.6 and 198 cm³ to prevent observation of size effects in the HL test. According to Çelik et al. [17], for axial and diameter measurements to be performed in core samples, the L/D ratio should be ≥ 1.5 . Ulusay et al. [33] stated that the L/D ratio should be ≥ 1.0 for core samples.

Determining the effect of sample size on the HL values of rocks, along with identifying the optimum sample size,

carries great importance in terms of evaluating the suitability and applicability of HL standards to be developed for rocks. Although numerous studies have investigated the effect of sample size on HL measurements using core samples, studies involving cubic samples remain limited. Moreover, previous studies have predominantly focused on rock groups characterized by relatively high strength values. Therefore, the first stage of this study aimed to investigate the variation in HL values of cubic samples with edge lengths ranging from 3 to 10 cm, prepared from 10 different pyroclastic rocks covering a wide range of physical and strength properties, and to determine the optimum sample size for HL testing.

2 Material and method

2.1 Material

In this study, rock sampling areas were chosen as rock quarries where magmatic-derived rock units' outcrop, that are used or could be used as construction stones, located in the Aksaray, Kayseri, Konya, Niğde and Nevşehir provinces in central Anatolia. Samples were taken from 10 different pyroclastic rocks with different physico-mechanical properties (particle size, density, porosity, etc.), thought to be suitable for the aim of the study, from these sample locations (Table 1).

2.2 Method

With the aim of determining the Leeb hardness values according to different dimensions and physical features of pyroclastic rocks used in the study, at least 3 block samples were created with minimum $30 \times 30 \times 50$ cm dimensions for each rock. Then, 24 (3×8) cube samples were prepared with edge lengths of 3 cm, 4 cm, 5 cm, 6 cm, 7 cm, 8 cm, 9 cm and 10 cm for each rock group according to the methods stated in TS EN-1936 [34] from these block

samples (Fig. 1(a)–(b)). For all rock groups, 240 ($3 \times 8 \times 10$) cube samples were prepared (Fig. 1(c)).

From these prepared samples, the samples with edge length 7 cm were used to determine the dry density and porosity values for each rock group according to the method recommended in TS EN-1936 [34] (Fig. 1(d)–(e)). P -wave velocity (V_p) values were identified based on standards stated in ASTM E494-10 [35]. In this experiment, a Proceq brand Pundit PL-200 model device was used (Fig. 1(f)). For each sample, measurements were repeated three times. Then the mean of these values was taken and the V_p value for the sample was calculated. For determination of the physical features of each rock group, 3 cube samples were used. Though the ASTM A956 [36] standard is used for the determination of HL values for steel products, there is still no standard developed for rocks. In this study, the approach recommended by İnce and Bozdağ [1] was used when determining HL values. In this study, an Insize brand test device was used for HL measurements (Fig. 1(g)). For measurements, a D -probe with 11 Nmm impact energy was used. This device has a HL measurement interval from 0 to 999, with accuracy value of ± 6 HL. Before determining the HL value of rocks, the device was calibrated using the calibration anvil. When determining the HL values for different cube sizes in each rock group, samples were fully dry and 3 cube samples were used. For each cube sample, the average of values measured at 20 different points on different surfaces was taken and the HL value defined for each cube sample. Later, the mean HL values were calculated for the 3 cube samples with the same size belonging to the same rock group. With the aim of determining the mineralogical and petrographic features of the rocks used in the study, three thin sections were prepared for each rock group according to the methods recommended in TS EN-12407 [37]. Then a Leica brand DM 2700 P model polarizing microscope was used to investigate the sections and textural definitions were made.

3 Results and discussion

3.1 Mineralogical and petrographic properties of rocks

The mineralogical and petrographic features of the pyroclastic samples used in this study are given in Table 2. Thin section investigation of the samples found the main mineralogical composition was volcanic glass, plagioclase, biotite, rock fragments, quartz and opaque minerals (Fig. 2 and Table 2). The macro and micro appearance of the pyroclastic rocks is given in Fig. 2. Among the samples, sample P2 was named

Table 1 Location and macro-features of the samples

Sample	Location	Colour	Particle size
P1	Kayseri	Light pink	Fine
P2	Kayseri	Gray	Fine
P3	Kayseri	Black	Coarse
P4	Kayseri	Pink	Fine
P5	Aksaray	Gray	Coarse
P6	Niğde	Gray	Medium
P7	Kayseri	Burgundy	Medium
P8	Nevşehir	Yellow	Medium
P9	Nevşehir	Gray	Very coarse
P10	Konya	Yellow	Very coarse

Particle size: fine (< 1 mm), medium (1–5 mm), coarse (5 mm–3 cm), very coarse (> 3 cm)

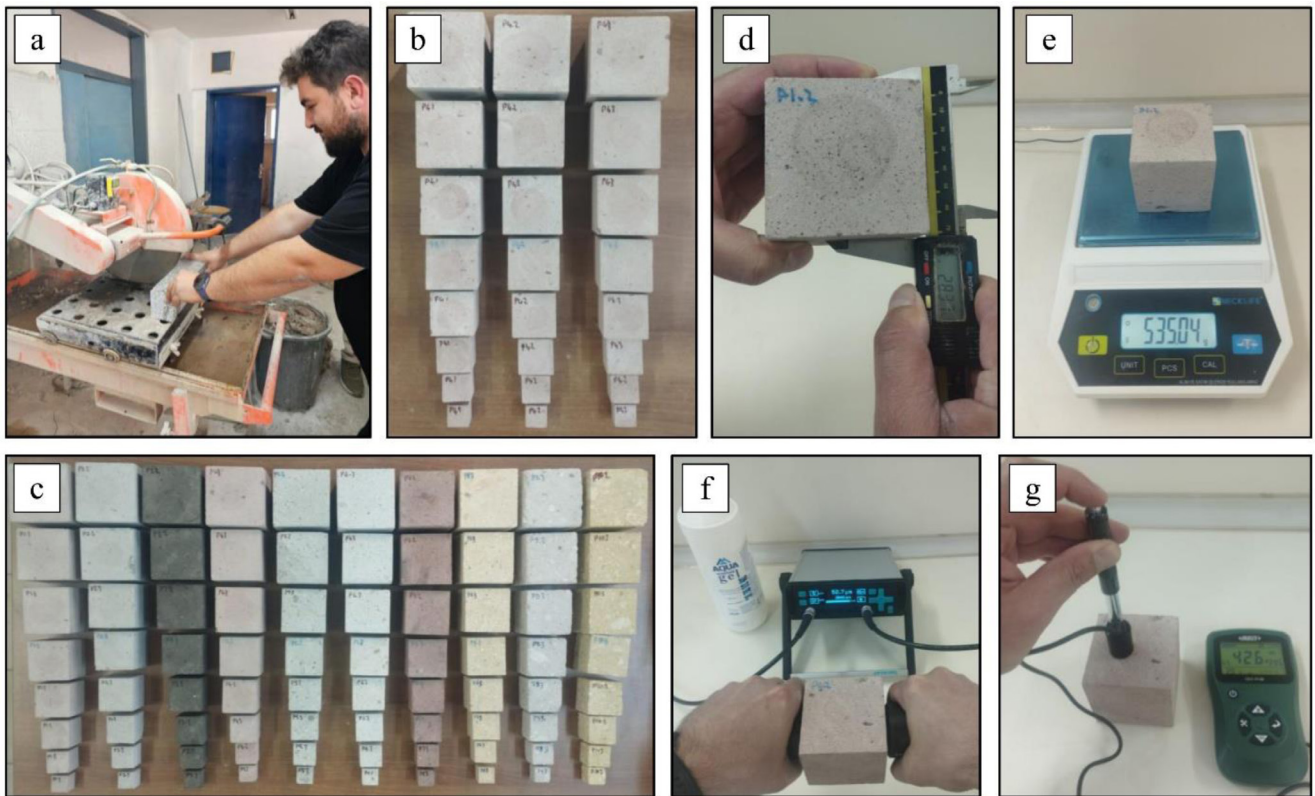


Fig. 1 The sample preparation and experiment stage: (a) block cutting, (b) cube samples with different sizes, (c) different samples used in the study, (d) measurement with calipers, (e) mass measurement, (f) *P*-wave velocity measurement, (g) Leeb hardness measurement

Table 2 Petrographic and mineralogical features of the examined samples

Sample No	Mineralogical composition - %	Texture	Rock name *
P1	66 Vg, 22 Pl, 4 Hbl, 4 Cpx, 3 Qtz and 1 Om	Hyaline porphyric	Vitric tuff
P2	49 Vg, 25 Pl, 14 Qtz, 6 Cpx, 5 Hbl and 1 Om	Hyaline porphyric	Crystal tuff
P3	66 Vg, 20 Pl, 5 Bt, 5 Hbl, 3 Cpx, and 1 A	Hyaline porphyric	Vitric tuff
P4	68 Vg, 17 Pl, 10 Qtz, 2 Cpx, 2 Bt and 1 Om	Hyaline porphyric	Vitric tuff
P5	57 Vg, 20 Pl, 14 Qtz, 5 Bt, 3 Hbl and 1 Om	Hyaline porphyric	Vitric tuff
P6	61 Vg, 20 Pl, 10 Qtz, 5 Bt, 3 Rf and 1 Om	Hyaline porphyric	Vitric tuff
P7	55 Vg, 21 Pl, 8 Qtz, 7 Rf, 5 Cpx, 3 Bt and 1 Om	Hyaline porphyric	Vitric tuff
P8	51 Vg, 19 Pl, 12 Qtz, 10 Rf, 7 Cal and 1 Om	Hyaline porphyric	Vitric tuff
P9	66 Vg, 14 Pl, 10 Rf, 5 Qtz, 4 Bt and 1 Om	Hyaline porphyric	Vitric tuff
P10	47 Vg, 33 Rf, 10 Pl, 6 Qtz, 3 Bt and 1 Om	Hyaline porphyric	Vitric tuff

Bt: biotite, Cal: calcite, Cpx: clinopyroxene, Hbl: hornblende, Om: opaque minerals, Pl: plagioclase, Qtz: quartz, Rf: rock fragment, Vg: volcanic glass. * Classified according to Schmid [33].

crystal tuff, while the other samples were named vitric tuff, according to Schmid [38] (Fig. 3). Apart from sample P6, flame structures were observed in all rocks. All samples had hyaline porphyric texture.

3.2 Physical properties of rocks

Values for the physical features (dry density, porosity, water absorption by weight, and *P*-wave velocity) obtained from the pyroclastic rocks used in the study and data from statistical analyses are given in Table 3. The dry

density values for pyroclastic rocks used in the study varied from 1.09-1.79 g/ cm³, while porosity values varied from 26.48% to 41.12%. According to NBG [39] dry density classification, rock samples used in the study were in the "very low" density rock class. Based on the NBG [39] porosity classification, rocks used in the experiments had "very high" porosity rock features. The water absorption values by weight for these rocks were between 14.79% and 37.01%. For pyroclastic rocks, the *P*-wave velocity values varied from 1.35 km/s to 2.57 km/s.

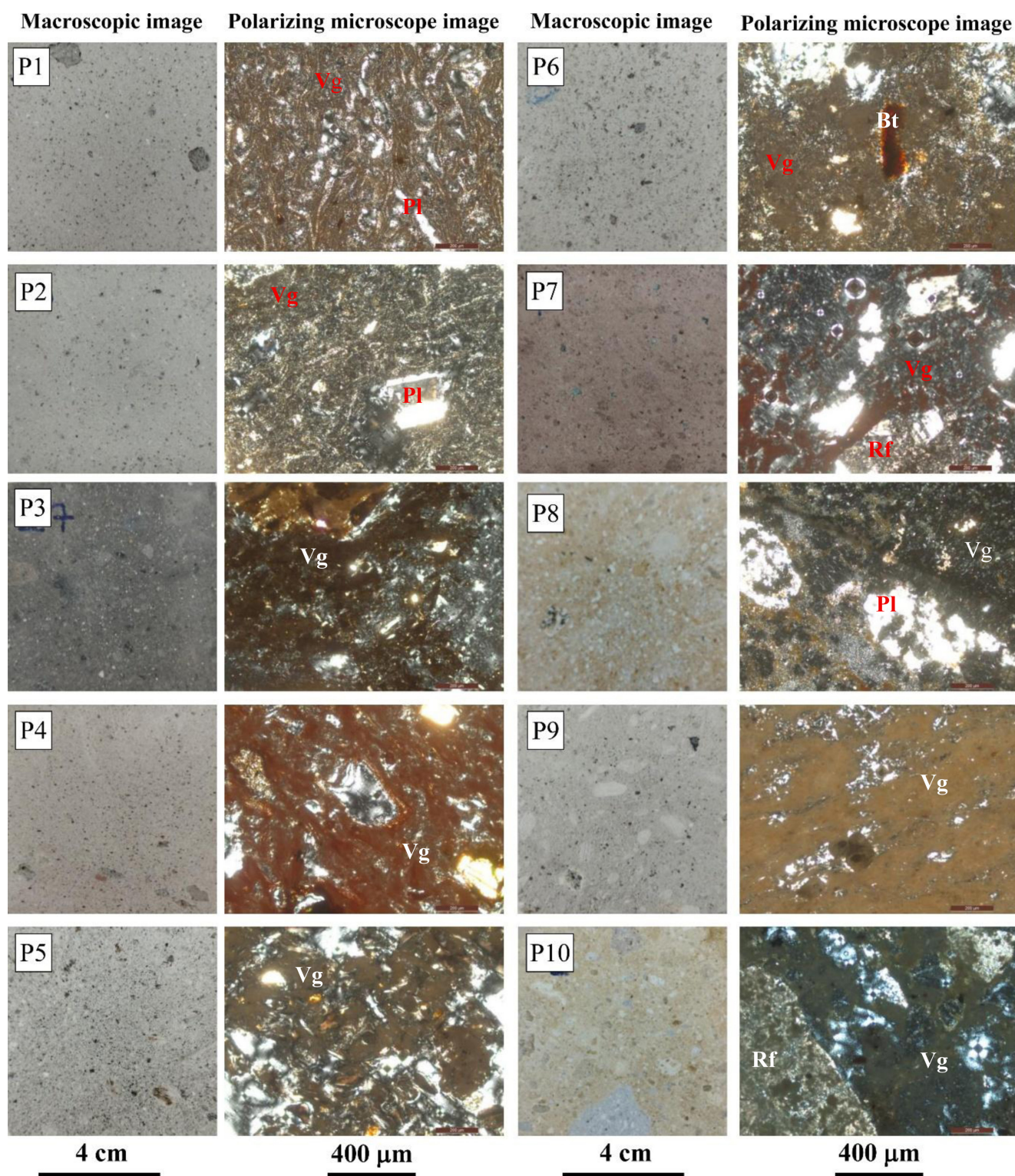


Fig. 2 Macro and micro views of pyroclastic rocks (Bt: biotite, Pl: plagioclase, Rf: rock fragment and Vg: volcanic glass)

3.3 The effect of the size factor on Leeb hardness in pyroclastic rocks

In this study, a total of 240 ($10 \times 8 \times 3$) cube samples were used with edge lengths of 3 cm, 4 cm, 5 cm, 6 cm, 7 cm, 8 cm, 9 cm and 10 cm from 10 different rock types. The homogeneity of the distribution of HL measurement points on the

surface was carefully checked to increase reliability of measurements. For each sample, the rebound hardness values were recorded systematically and the statistical data for the measurements are given in Table 4.

The variation in HL values with the effect of size of the samples is given in Fig. 4. The data shows clear

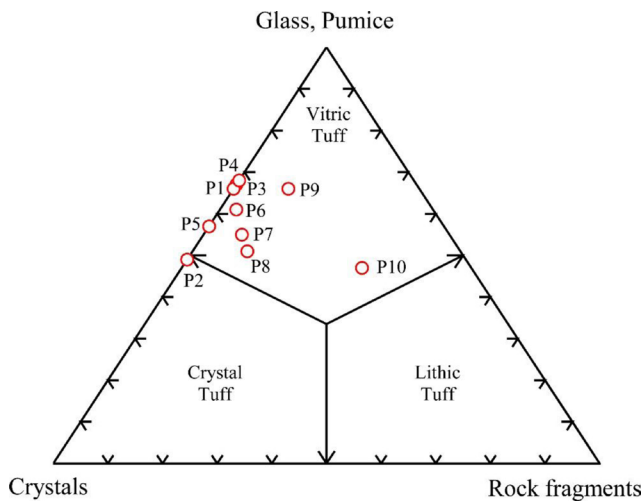


Fig. 3 Classification of pyroclastic rocks according to Schmid [38]

Table 3 Physical properties and statistical data of rocks

Rock name	ρ_d (g/cm ³)	n (%)	W_a (%)	V_p (km/s)
P1	1.48	29.64	20.10	1.85
P2	1.57	26.69	17.04	1.80
P3	1.26	36.97	29.52	1.94
P4	1.11	41.12	37.01	1.35
P5	1.52	28.60	18.83	1.69
P6	1.47	32.72	22.34	1.85
P7	1.79	26.48	14.79	2.57
P8	1.64	27.61	16.80	2.28
P9	1.09	35.82	33.00	1.43
P10	1.33	30.58	23.08	2.30
Minimum	1.09	26.48	14.79	1.35
Maximum	1.79	41.12	37.01	2.57
Mean	1.42	31.62	23.25	1.91
Standard deviation	0.23	4.93	7.50	0.39

ρ_d : dry density, n : porosity, W_a : water absorption by weight, V_p : P-wave velocity

fluctuations in rebound hardness values for samples with smaller sizes. This situation is associated with the impact energy not being sufficiently absorbed in limited volumes and the surface characteristics becoming more dominant in the measurements. With the increase in sample size, the mean trend of the HL values was observed and how the standard deviation values change was revealed in detail. For larger samples, the rebound hardness values appeared to be more consistent as a result of the impact energy being spread over a larger volume.

Among pyroclastic rock samples, for rocks numbered P1, P2, P4, P6, P7 and P8, no clear variation was observed for the HL values in cube samples with 8–10 cm edge length (Fig. 4). Fig. 5 was prepared to show the variation in these samples more clearly. When Fig. 5 is investigated,

a stable Leeb hardness value was obtained in cube samples with edge length larger than 8 cm. In this rock group, cube samples with edge length shorter than 8 cm were identified to display a reducing trend in HL values. As the edge lengths of the samples increased, the degree of effect of the size factor in the rocks reduced. The statistical results in Table 4 show the standard deviation values for HL measurements increase as the sample size decreases. Contrary to this, the standard deviation values were lower for sample sizes of 8 cm or more. This finding supports the general trend observed in Fig. 4 in quantitative terms.

For samples P3, P5, P9 and P10, there was no significant correlation identified between the change in cube size with HL values (Fig. 5). This outlier behaviour is thought to be due to the heterogeneous structure developing in these samples linked to the irregular distribution of rock components (rock fragments, pumice, and phenocrysts) (Fig. 6). Previous studies have also indicated that such mineralogical and textural heterogeneity can influence Leeb hardness measurements [1, 8, 28, 30]. İnce et al. [8] reported that the coexistence of surface components with different hardness levels in pyroclastic rocks can increase the scatter of HL measurements, whereas Karakaya et al. [30] showed that HL values tend to increase with increasing proportion of harder minerals at the rock surface. Similar observations were reported by İnce and Bozdağ [1] and Balcı and İnce [28], who emphasized the sensitivity of Leeb hardness measurements to local variations in rock surface characteristics. This sensitivity is particularly relevant to the present study because the D-probe applies the impact over a relatively small contact area (3 mm in diameter). Consequently, even minor variations in the material encountered by the probe can affect the measured HL value. In pyroclastic rocks, the presence of rock fragments, mineral grains, and volcanic glass with different hardness characteristics may therefore increase the local variability of HL measurements, which can be reflected in greater scatter and higher standard deviation values.

The findings show that to be able to obtain reliable and repeatable results for Leeb hardness measurements of pyroclastic rocks, the critical minimum edge length (minimum reliable sample edge length) is nearly 8 cm for cube samples. Fig. 7 was prepared with the aim of evaluating the reliability of the optimum cube edge length identified for pyroclastic rocks. On this graphic, samples P3, P5, P9 and P10, without a significant correlation between the variation in cube size with HL values, were excluded from the analysis. The graph reveals the relationship between

Table 4 Statistical data on HL values measured in pyroclastic rocks

Sample No.	Statistical data	One edge length of the cube (cm)							
		3	4	5	6	7	8	9	10
P1	Minimum	207.00	253.00	355.00	354.00	358.00	417.00	392.00	396.00
	Maximum	356.00	478.00	449.00	452.00	498.00	479.00	491.00	503.00
	Mean	297.30	380.40	402.10	388.40	426.70	445.50	451.60	450.70
	Standard deviation	52.45	75.34	36.28	31.43	44.83	24.16	33.47	33.43
P2	Minimum	258.00	315.00	400.00	352.00	400.00	435.00	442.00	427.00
	Maximum	395.00	396.00	572.00	552.00	557.00	538.00	556.00	557.00
	Mean	326.56	345.89	458.56	466.00	479.22	485.11	492.78	487.67
	Standard deviation	47.04	31.76	59.21	64.78	43.55	33.24	42.41	42.59
P3	Minimum	211.00	234.00	238.00	271.00	219.00	238.00	336.00	300.00
	Maximum	364.00	287.00	326.00	322.00	354.00	450.00	411.00	370.00
	Mean	287.78	267.22	296.56	292.00	299.11	322.00	360.89	334.67
	Standard deviation	46.95	19.38	29.72	17.64	39.72	61.82	24.11	23.14
P4	Minimum	230.00	181.00	289.00	291.00	242.00	303.00	308.00	320.00
	Maximum	286.00	310.00	344.00	363.00	349.00	420.00	427.00	396.00
	Mean	254.00	251.33	320.11	319.67	284.89	355.67	358.00	358.33
	Standard deviation	21.30	37.05	16.83	20.14	31.98	35.92	42.19	23.05
P5	Minimum	173.00	190.00	166.00	200.00	249.00	266.00	178.00	282.00
	Maximum	447.00	363.00	400.00	365.00	346.00	655.00	396.00	465.00
	Mean	274.90	276.10	312.60	295.40	299.50	363.80	299.20	393.80
	Standard deviation	89.29	53.74	69.21	44.97	29.90	108.29	69.92	52.20
P6	Minimum	148.00	202.00	204.00	190.00	254.00	237.00	233.00	214.00
	Maximum	276.00	326.00	341.00	391.00	373.00	408.00	439.00	402.00
	Mean	218.70	268.50	295.03	308.83	327.87	330.70	335.93	332.70
	Standard deviation	34.31	30.94	33.58	50.81	35.67	46.33	43.08	44.19
P7	Minimum	129.00	121.00	275.00	204.00	443.00	435.00	464.00	424.00
	Maximum	540.00	593.00	590.00	624.00	788.00	726.00	672.00	625.00
	Mean	361.63	418.80	467.00	483.60	556.03	567.20	573.70	560.50
	Standard deviation	101.91	112.51	83.56	86.96	82.10	85.20	60.17	56.51
P8	Minimum	218.00	260.00	223.00	257.00	275.00	297.00	255.00	273.00
	Maximum	300.00	323.00	323.00	400.00	368.00	364.00	419.00	405.00
	Mean	256.90	293.50	286.40	323.50	328.80	335.60	334.50	336.20
	Standard deviation	27.18	19.17	28.47	39.01	30.69	24.73	30.10	28.30
P9	Minimum	166.00	160.00	208.00	135.00	95.00	135.00	173.00	236.00
	Maximum	248.00	240.00	338.00	309.00	294.00	311.00	496.00	557.00
	Mean	206.60	199.40	261.10	236.50	227.80	252.60	280.10	308.90
	Standard deviation	25.46	24.84	40.16	50.97	70.34	55.95	85.32	90.74
P10	Minimum	88.00	94.00	135.00	201.00	194.00	235.00	148.00	214.00
	Maximum	348.00	458.00	758.00	620.00	715.00	767.00	579.00	695.00
	Mean	217.20	267.10	337.30	353.20	327.30	380.60	408.50	397.30
	Standard deviation	92.77	122.58	172.94	116.94	160.27	160.18	142.50	163.22

normalized values obtained by proportioning the HL values measured for different cube edge lengths for each rock with the HL value obtained with the minimum reliable sample edge length and the edge lengths. As a result of

investigating Fig. 7, it was understood that there was no clear variation in HL values for samples sizes above the minimum reliable sample edge length. Additionally, it was observed that the normalized HL values approached 1 at

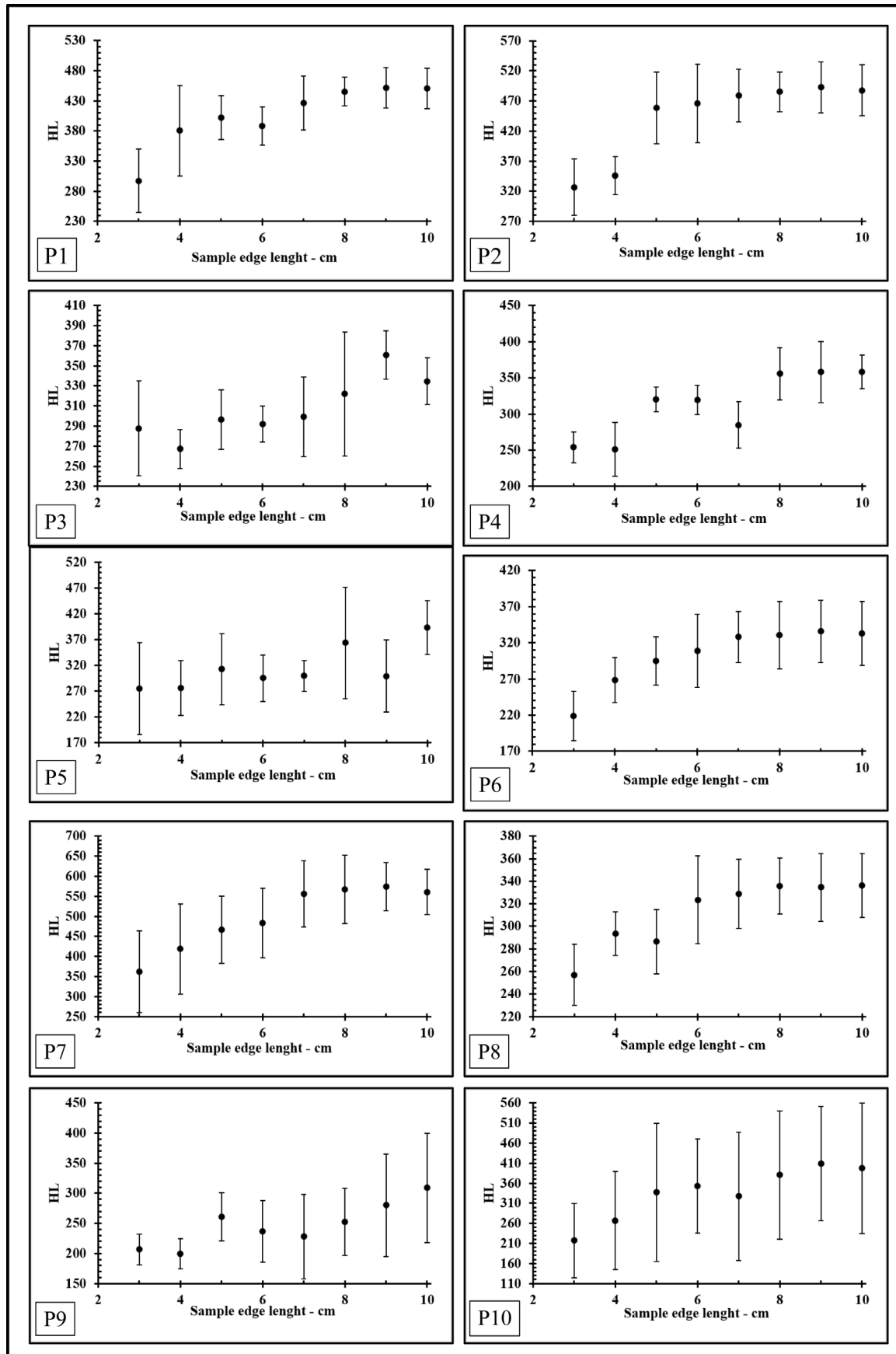


Fig. 4 Changes in HL values according to the sample size

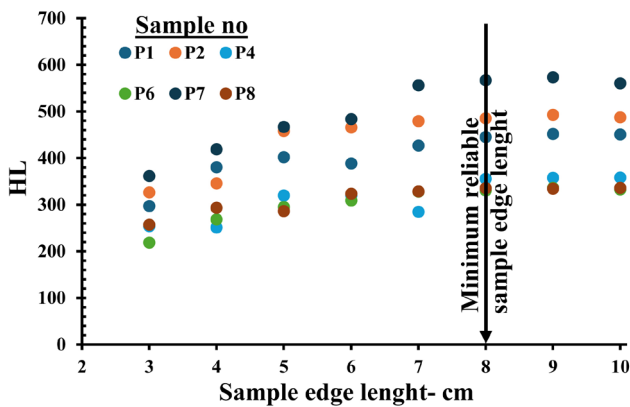


Fig. 5 Changes in HL values according to sample size in pyroclastic rocks (Except for P3, P5, P9, and P10 samples)

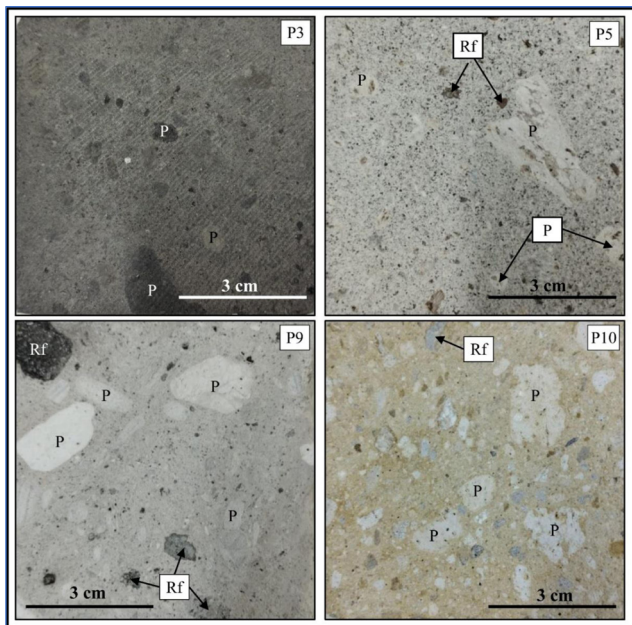


Fig. 6 Rock components that affect HL value (Rf: rock fragment and P: pumice)

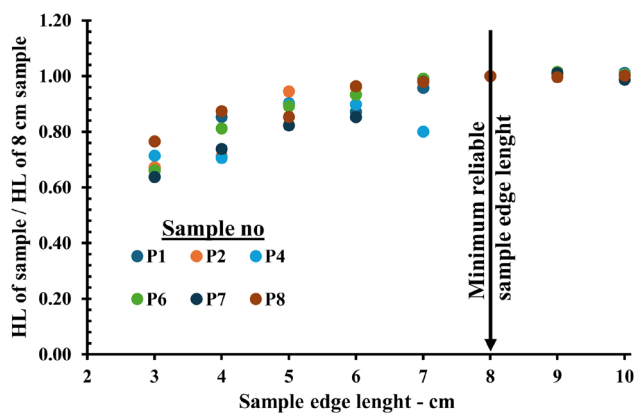


Fig. 7 Influence of sample size on the HL in pyroclastic rock (Except for P3, P5, P9, and P10 samples)

the minimum reliable sample edge length in all samples. Therefore, to minimize size effects and improve comparability with other studies, cubic samples should have an edge length equal to or greater than the minimum reliable sample edge length of 8 cm.

4 Conclusions

This study was performed with the aim of determining the variation in HL values with the effect of size in cube samples with different edge lengths (3–10 cm) prepared from 10 pyroclastic rocks with a broad range of physical features. The results obtained from this research may be summarized as follows:

- The mineralogical and textural features of the pyroclastic rocks were identified. Sample P2 was crystal tuff, while the other samples had the features of vitric tuff. All samples had hyaline porphyric texture.
- This study examined pyroclastic rocks covering a wide range of dry density (1.09–1.79 g/cm³), porosity (26.48–41.12%), and *P*-wave velocity (1.35–2.57 km/s).
- The results of the research revealed that for the size factor not to affect the HL test applied to cube samples from pyroclastic rocks, the minimum reliable sample edge length required is 8 cm.
- In experimental studies, for samples below the edge length of 8 cm in cube samples, the difference between minimum and maximum values obtained from the HL test increases and linked to this, the standard deviation values clearly increase.
- In situations where the diameter of the piston probe in the Leeb hardness device is equal to the dimensions of components comprising pyroclastic rocks, it is necessary to take great care when determining the HL value.
- Another finding of this study is that pyroclastic rocks containing relatively large rock fragments and pumice with contrasting surface hardnesses and sizes greater than the piston diameter are not recommended for HL testing.

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