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Influence of Surface Roughness on Mechanical Properties of Two Computer-aided Design/ Computer-aided Manufacturing (CAD/CAM) Ceramic Materials

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Clinical Relevance

Dental practitioners who use chairside computer-aided design/computer-aided manufacturing (CAD/CAM) technology should carefully finish and polish their CAD/CAM ceramic restorations as the present study showed that a decrease in surface roughness improved mechanical properties, that is, led to an increase in surface hardness, elastic modulus, and flexural strength for both CAD/CAM ceramic materials.

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SUMMARY

The aim of this study was to evaluate the influence of surface roughness on surface hardness (Vickers; VHN), elastic modulus (EM), and flexural strength (FLS) of two computer-aided design/computer-aided manufacturing (CAD/CAM) ceramic materials. One hundred sixty-two samples of VITABLOCS Mark II (VMII) and 162 samples of IPS Empress CAD (IPS) were ground according to six standardized protocols producing decreasing surface roughnesses (n=27/group): grinding with 1) silicon carbide (SiC) paper #80, 2) SiC paper #120, 3) SiC paper #220, 4) SiC paper #320, 5)

SiC paper #500, and 6) SiC paper #1000. Surface roughness (Ra/Rz) was measured with a surface roughness meter, VHN and EM with a hardness indentation device, and FLS with a three-point bending test. To test for a correlation between surface roughness (Ra/Rz) and VHN, EM, or FLS, Spearman rank correlation coefficients were calculated. The decrease in surface roughness led to an increase in VHN from (VMII/IPS; medians) 263.7/256.5 VHN to 646.8/601.5 VHN, an increase in EM from 45.4/41.0 GPa to 66.8/58.4 GPa, and an increase in FLS from 49.5/44.3 MPa to 73.0/97.2 MPa. For both ceramic materials, Spearman rank correlation coefficients showed a strong negative correlation between surface roughness (Ra/Rz) and VHN or EM and a moderate negative correlation between Ra/Rz and FLS. In conclusion, a decrease in surface roughness generally improved the mechanical properties of the CAD/CAM ceramic materials tested. However, FLS was less influenced by surface roughness than expected.

INTRODUCTION

Direct ceramic restorations produced with chairside computer-aided design/computer-aided manufacturing (CAD/CAM) systems are milled by burs coated with diamond abrasive particles of 50- to 60-μm grit size, for example (for Sirona CEREC system; diamond abrasive particles of D64 [$\approx$ mesh 260] grit size; Sirona, Bensheim, Germany). As a result, these ceramic restorations initially show a high surface roughness. The high surface roughness needs to be reduced—normally obtained through finishing and polishing—since surface roughness greatly influences esthetical, biological, and mechanical properties of ceramic restorations. Restoration surfaces of high roughness tend to increase discoloration,[1] may facilitate plaque accumulation,[2,3] and lead to abrasion and increased wear of antagonists.[4,5] Finally, high surface roughness has generally been described to negatively influence porcelain strength.[6–9] Literature is sparse as to the effect of surface roughness on mechanical properties of CAD/CAM ceramic materials. Therefore, the present study aimed to investigate the influence of different surface roughnesses (Ra and Rz) on surface hardness (Vickers; VHN), elastic modulus (EM), and flexural strength (FLS) of one feldspathic and one leucite-reinforced CAD/CAM ceramic material.

The working hypothesis to be tested was that surface roughness influenced mechanical properties with a strong negative correlation between surface roughness and VHN, EM, and FLS for a given ceramic material.

METHODS AND MATERIALS

Sample Preparation

A total of 324 ceramic samples were produced. One hundred sixty-two samples were made of a feldspathic CAD/CAM ceramic material (VITABLOCS Mark II for CEREC; size I8, Vita Zahnfabrik, Bad Säckingen, Germany), and 162 were made of a leucite-reinforced ceramic material (IPS Empress CAD for CEREC; size I8, Ivoclar Vivadent AG, Schaan, Liechtenstein). Specifications of the two ceramic materials are listed in Table 1. To obtain the samples, 81 blocks of each ceramic material were cut in half, and the metal stubs were removed (Isomet Low Speed Saw, Isomet, Lake Bluff, IL). Each cut surface was then ground according to one of six standardized grinding protocols. The standardized grinding was performed with a grinding machine (Tegra Pol 15/Tegra Pol 1, Struers, Ballerup, Denmark) and grinding papers of six different grit sizes (silicon carbide [SiC] papers, diameter 200 mm, Struers; Table 2) to obtain six groups of decreasing surface roughness (n=27/group). All grinding protocols were carried out under water cooling at a speed of 200 rpm for 15 seconds and with a pressure of 15 N. Three samples could be ground simultaneously using mountings made of a self-curing acrylic resin (Paladur, Heraeus Kulzer, Hanau, Germany) to fix the samples in the machine. The SiC paper was changed after each group of three samples had been ground. The samples were then ultrasonically cleaned (TUC-150, Telsonic AG, Bronschhofen, Switzerland) for 1 minute in 100% ethanol and air dried.

Measurement of Surface Roughness

The ground surfaces of the ceramic samples were profilometrically analyzed with a surface roughness meter (Perthometer S2, Mahr GmbH, Göttingen, Germany): the average surface roughness (Ra; μm) and the arithmetic mean height of the surface profile (Rz; μm) were measured. Three measurements per sample were determined over a transverse length of Lt=5.600 mm, with a cutoff value of 0.8 mm and a stylus speed of 0.5 mm/second. The sample was turned 45° for each new measurement. From the three Ra and Rz values per sample, a mean Ra and a mean Rz value were calculated. During the experimental period, the surface roughness meter was monitored with a calibration device (Mahr GmbH) on each day prior to measuring.

Table 1: *Ceramic Materials Used (Manufacturer Information)*

Material	Brand Name (Manufacturer)	Lot No.	Shade	Average Particle Size, μm	Composition	% by Weight
Feldspathic ceramic material	VITABLOCS Mark II for CEREC (Vita, Bad Säckingen, Germany)	0000100038	2M3C	4	SiO_2	56–64
					Al_2O_3	20–23
					Na_2O	6–9
					K_2O	6–8
Leucite-reinforced ceramic material	IPS Empress CAD for CEREC (Ivoclar Vivadent AG, Schaan, Liechtenstein)	N42417	HT A3	1–5	SiO_2	60–65
					Al_2O_3	16–20
					Na_2O	3.5–6.5
					K_2O	10–14

Measurement of VHN and EM

Six VHN and six EM (GPa) measurements per ceramic sample were made simultaneously on the ground surfaces with a hardness indentation device at a force of 10 g for 15 seconds (Fischerscope HM2000, Helmut Fischer GmbH, Sindelfingen, Germany). The six measurements were made in two parallel lines of three measurements each. Each of the two lines was located at a distance of 1 mm from two opposing edges. Programming of the hardness indentation device and reproducible placement of the sample ensured that the indentations were made within exactly the same position on all samples. From the six VHN and EM values per sample, a mean VHN and a mean EM value were calculated.

Measurement of FLS

The two parallel lines along which the indentations had been made on each ceramic sample were marked with a felt pen. Then, the sample was mounted in a diamond blade low-speed saw (Isomet Low Speed Saw, Isomet) to cut one plate of approximately 2-mm thickness from each ceramic sample (range: 1.8-2.2 mm; mean value [standard deviation], 2.03 mm [0.8]). The actual thickness of each ceramic plate was measured with a digital caliper (Mitutoyo IP 65, Kawasaki, Japan) for later calculation of the FLS (MPa). The plates were then ultrasonically cleaned for 1 minute in deionized water and air dried. The plates were placed in a Zwick Z010 universal testing machine (Zwick GmbH & Co, Ulm, Germany) fitted with a custom-made, three-point bending jig (M. E. Mueller Institute, Bern, Switzerland). The ground surface was orientated toward the bearers of the three-point bending jig, ensuring that the felt pen–marked lines were parallel to the bearers. Thus, the plates were loaded from the nonground surface at a

Table 2: *The Six Groups of Decreasing Surface Roughness for Both Ceramic Materials (n=27/Group and Material) According to Standardized Grinding with Silicon Carbide Papers of Six Different Grit Sizes*

Group	Grit # (DIN)	US-Standard (ANSI)	Abrasive Particle Size, μm (Manufacturer Information)
1	80	80	~200
2	120	100–120	~125
3	220	220	~68
4	320	~280	~46
5	500	~360	~30
6	1000	500	~18

Table 3: *Surface Roughness of the Six Groups (Ra/Rz; Minima [Min], Median, and Maxima [Max]) and Decrease in Ra/Rz Compared With the Antecedent Group (Except Group 1) for Both Ceramic Materials*

	Group 1			**Group 2**				**Group 3**				**Group 4**			
	Min	**Median**	Max	Min	**Median**	Max	Decrease	Min	**Median**	Max	Decrease	Min	**Median**	Max	Decrease
Feldspathic ceramic material															
Ra, μm	1.17	**1.68**	2.15	0.82	**1.11**	1.52	−0.57	0.41	**0.56**	0.76	−0.55	0.30	**0.40**	0.58	−0.16
Rz, μm	7.63	**9.95**	12.77	5.46	**7.47**	10.00	−2.48	3.07	**4.00**	5.06	−3.47	2.23	**2.95**	4.26	−1.05
Leucite-reinforced ceramic material															
Ra, μm	1.17	**1.57**	2.29	0.73	**1.11**	1.40	−0.46	0.37	**0.53**	0.73	−0.58	0.25	**0.38**	0.52	−0.15
Rz, μm	7.63	**10.18**	14.30	5.15	**7.31**	8.88	−2.87	2.74	**3.80**	5.43	−3.51	1.72	**2.67**	3.89	−1.13

cross-head speed of 1.0 mm/minute. The breaking load (F_{max}; N) was recorded (testXpert software, V9.0, Zwick GmbH & Co), and the FLS of each plate was calculated in analogy to ISO 6872:[10] $FLS = 3F_{max}l / 2bd^2$, where l (mm) was the center-to-center distance between bearers (6.4 mm), b (mm) was the width of the plate (8.3 mm for VITABLOCS Mark II; 8.0 mm for IPS Empress CAD), and d (mm) was the thickness of the plate measured as described above.

Statistical Analysis

To test for a correlation between surface roughness (Ra/Rz) and VHN, EM, or FLS, Spearman rank correlation coefficients were calculated. Calculations were performed with R version 2.13.0 (The R Foundation for Statistical Computing, Vienna, Austria; www.R-project.org).

RESULTS

Surface roughness (Ra/Rz; minima, median, and maxima) as well as the decrease in Ra/Rz compared with the antecedent group (except group 1) is shown in Table 3 for both ceramic materials. The influence of surface roughness (Ra/Rz) on VHN, EM, and FLS of all samples are shown in Figure 1 for the feldspathic ceramic material and in Figure 2 for the leucite-reinforced ceramic material. In each figure, dots of the same color represent the ceramic samples of one group, with each dot indicating the surface roughness (Ra and Rz) and the corresponding VHN, EM, or FLS of one of the 27 ceramic samples in each of the six groups.

Spearman rank correlation coefficients over all six groups for a given material showed a strong negative correlation between surface roughness (Ra and Rz) and VHN or EM but only a moderate negative correlation between surface roughness (Ra and Rz) and FLS (Table 4).

DISCUSSION

In the present study, six groups of decreasing surface roughness were produced on two CAD/CAM ceramic materials by grinding of the ceramic samples with SiC papers. Group 1 intended to mimic the surface roughness of a dental ceramic restoration after the milling process by diamond burs during CAM. Groups 2 to 6 were produced according to the range of surface roughnesses (Ra/Rz) obtained in a previous study with different polishing methods, in which the same ceramic materials and the same profilometric measurement conditions were used.[11] Thus, group 2 showed Ra and Rz values very similar to those produced by a bur coated with diamond particles of 40-μm grit size, whereas group 6 showed Ra and Rz values very similar to those produced with superior polishing methods.

First, the present study showed a strong correlation between surface roughness and VHN, with decreasing surface roughness leading to increasing VHN. Clinically, an increase in VHN implies an increase in resistance to abrasion and thus to a decrease in wear on the surface of a ceramic restoration. An explanation for the correlation shown between surface roughness and VHN is that a high surface roughness implicates unevenness

Table 3: Extended.

Group 5				Group 6			
Min	**Median**	Max	Decrease	Min	**Median**	Max	Decrease
Feldspathic ceramic material							
0.19	**0.27**	0.36	−0.13	0.11	**0.15**	0.20	−0.12
1.46	**2.07**	2.99	−0.88	0.84	**1.14**	1.46	−0.93
Leucite-reinforced ceramic material							
0.17	**0.25**	0.34	−0.13	0.07	**0.15**	0.19	−0.10
1.42	**1.80**	2.48	−0.87	0.57	**1.02**	1.50	−0.78

with pronounced grooves (eg, scratches and undulations) on the surface of a material. Consequently, the tip of the hardness indentor gets into contact with the elevated parts of the rough surface first. However, the tip does not (or only toward the end of the measurement) reach the entire surface of a material including the surface at the bottom of the grooves. Hence, grooves did not account for the ceramic VHN measurement and thus led to lower VHN. In contrast, SiC paper with abrasive particles of small grit size led to a more planar surface with less pronounced grooves. A more planar surface offers continuous resistance to the entire tip of the indentor and thus leads to higher VHN. Although determination of VHN has been described as suitable for measuring the surface hardness of brittle materials such as ceramic materials,[12] VHN measurements on rough surfaces might not correspond to the actual hardness of the ceramic material but might rather characterize the topography of the surface, which can be regarded as a limitation of the method used in the present study. Moreover, it is unclear to what extent any effects of grinding influenced the VHN (eg, effects of compression/compaction[13,14] or thermal changes when grinding is performed with SiC papers comprising abrasive particles of small grit size).

Second, the present study showed a strong correlation between surface roughness and EM, with decreasing surface roughness leading to increasing EM. Clinically, an increase in EM implies a (relative) increase in stiffness or rigidity of a ceramic restoration and thus higher resistance to deformation. The correlation shown between surface roughness and EM may not be surprising considering that EM was simultaneously determined with the same hardness indentation device as was VHN. It remains to be investigated if the EM of a ceramic material determined by means of an indentor (ie, micromechanically determined on the surface) is indeed accurate and if it correlates with EM (macromechanically) determined by bending/tensile tests. Although not quantitatively confirmed, the slope of the stress-strain curves obtained during the measurements of FLS looked similar regardless of surface roughness, which suggests that the EM for a given ceramic material depends on material-dependent, intrinsic properties rather than on surface roughness.

Third, the present study generally showed that decreasing surface roughness led to increasing FLS, which is also supported by previous studies.[8,9,15] Clinically, an increase in FLS implies a higher resistance to chipping and fracture of a ceramic restoration and thus higher longevity. As reflected by the correlation shown in the present study, however, a decrease in surface roughness only moderately increased FLS. De Jager and coworkers concluded that although surface roughness primarily determined strength of a ceramic material, a decrease in strength may also occur when areas and concentrations of stress are present inside the ceramic material.[7] A limited influence of surface roughness on strength of ceramic materials was described in a study of Albakry and coworkers, who observed a poor correlation between surface roughness and FLS of two ceramic materials and concluded that not only surface roughness but also porosity, microstructural stresses, or surface and bulk defects may influence the FLS of ceramic materials.[14]

CONCLUSIONS

- Reducing the surface roughness generally improved the mechanical properties of the CAD/CAM ceramic materials tested. Therefore, direct ceramic restorations produced with chairside CAD/CAM systems need to be finished and polished carefully.
- The working hypothesis was partly accepted. Whereas the correlation between surface roughness and VHN or EM was indeed strong, the correlation between surface roughness and FLS was only moderate.
- The latter correlation indicates that FLS of the CAD/CAM ceramic materials tested might not have been solely influenced by surface roughness.

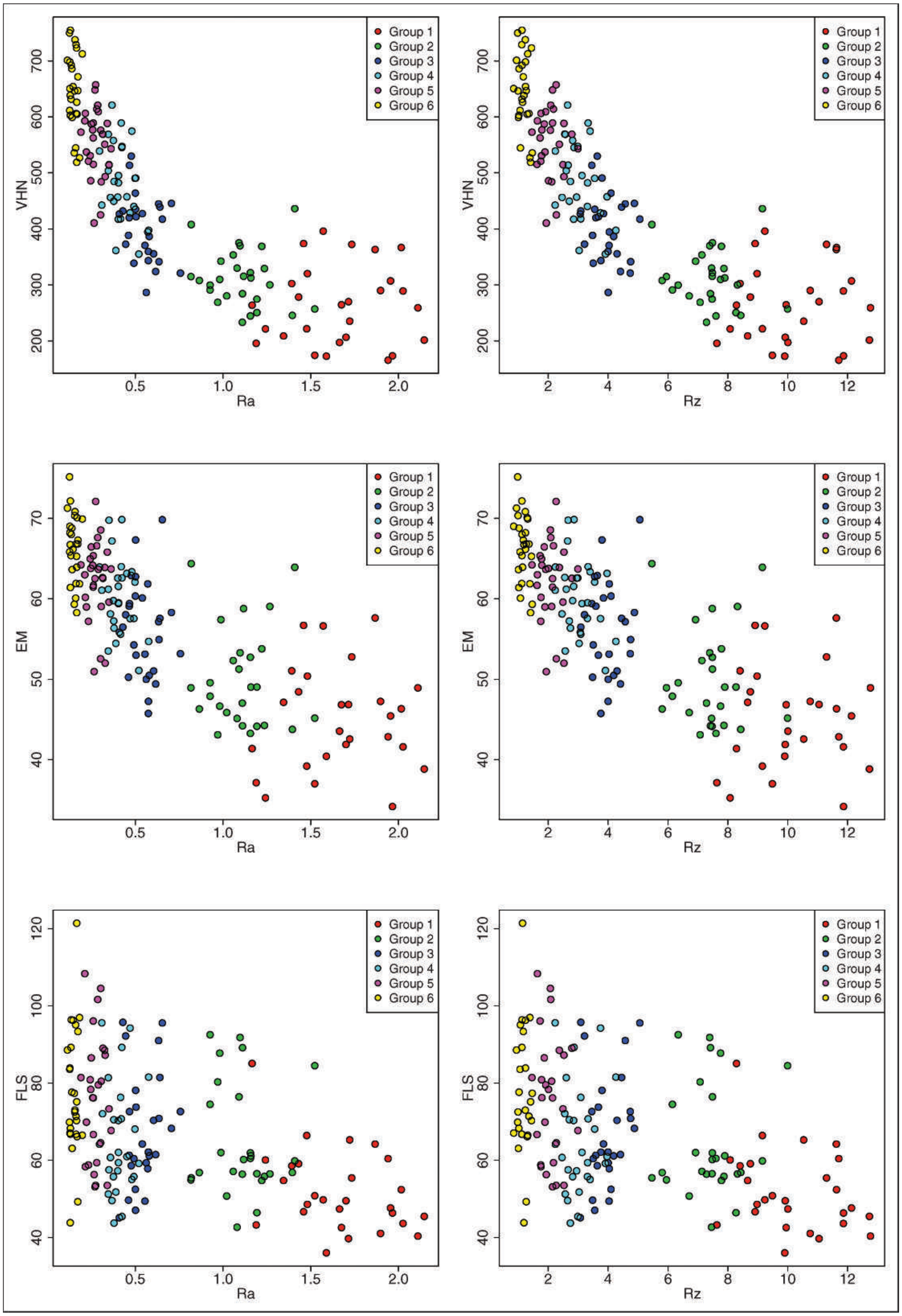

Figure 1. *Feldspathic ceramic material: surface roughness (Ra/Rz; μm) and surface hardness (Vickers; VHN), elastic modulus (EM; GPa), and flexural strength (FLS; MPa) of all samples in the six groups.*

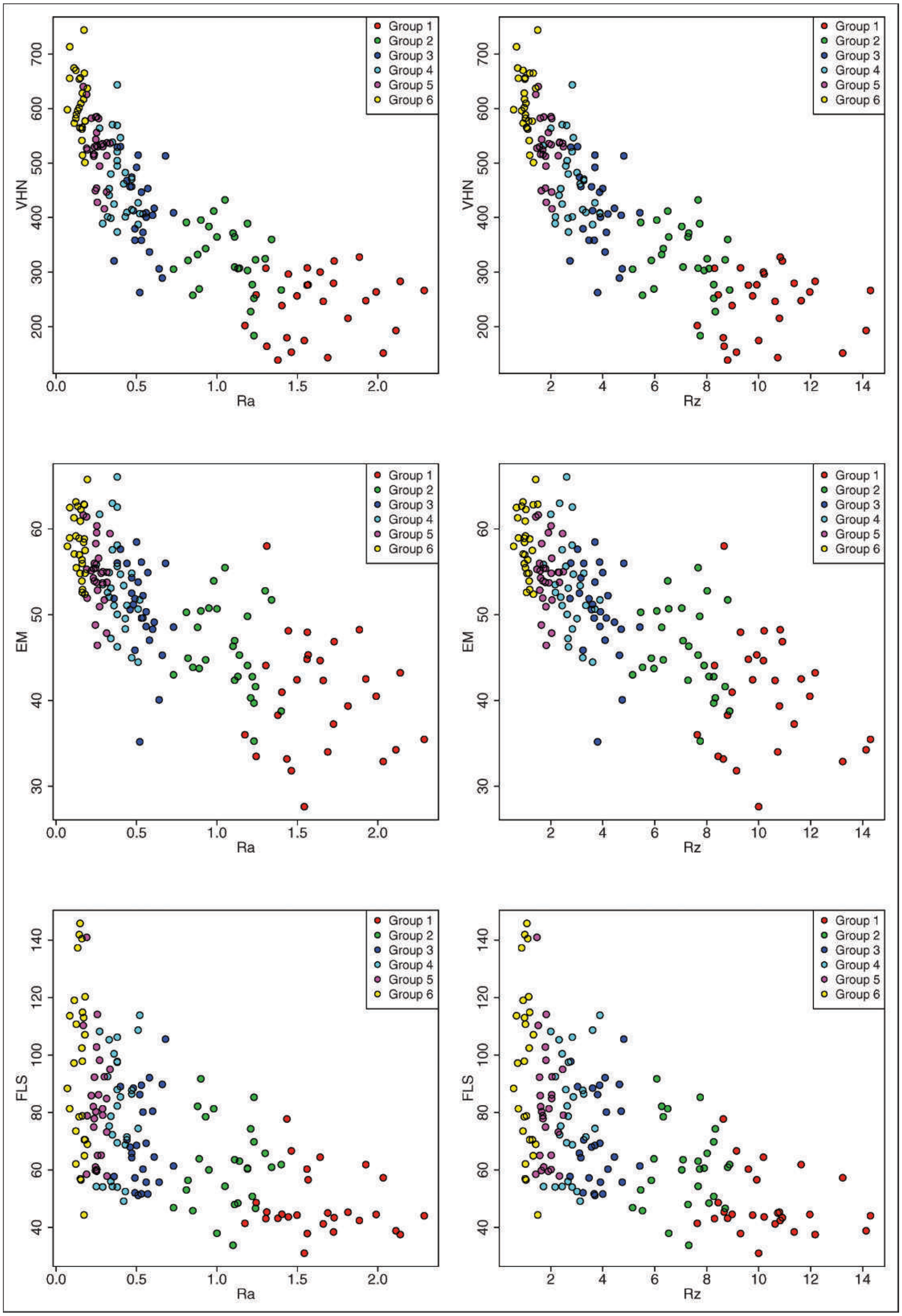

Figure 2. *Leucite-reinforced ceramic material: surface roughness (Ra/Rz; μm) and surface hardness (Vickers; VHN), elastic modulus (EM; GPa), and flexural strength (FLS; MPa) of all samples in the six groups.*

Table 4: *Correlation Between Surface Roughness (Ra/Rz) and Surface Hardness (Vickers; VHN), Elastic Modulus (EM), and Flexural Strength (FLS) for Both Ceramic Materials (Spearman Rank Correlation Coefficients Over All Six Groups for Both Ceramic Materials)*

Correlation	Spearman Rank Correlation Coefficient
Feldspathic ceramic material	
Ra: VHN	−0.9033
Rz: VHN	−0.9000
Ra: EM	−0.7943
Rz: EM	−0.7910
Ra: FLS	−0.4827
Rz: FLS	−0.4804
Leucite-reinforced ceramic material	
Ra: VHN	−0.9025
Rz: VHN	−0.9001
Ra: EM	−0.7856
Rz: EM	−0.7816
Ra: FLS	−0.6054
Rz: FLS	−0.6111

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Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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