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Effect of firing conditions, filler grain size and quartz content on bending strength and physical properties of sanitaryware porcelain

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Abstract

The effect of filler grain size, quartz content in the filler and firing conditions (sintering temperature, firing time) on the physical and mechanical properties of a sanitary-ware porcelain has been studied in the narrow range of values used by industrial practice. The investigation has been carried out using the Taguchi method for experimental design. Quartz grain size is the most important factor regarding the physical properties and dominates bending strength in two ways, directly by inducing compressive stresses to the vitreous phase and indirectly through the development of a favorable microstructure. The characteristics of the last are discussed in detail. The optimum grain size of quartz was found to be 5–20 μm. This results in 20–30% increase of bending strength compared to the reference porcelain. The results confirm the ''Matrix Reinforcement'' theory, however, the positive effect of mullite content on bending strength was not observed.

Keywords: Mechanical properties; Porcelain; Quartz; Taguchi method

1. Introduction

The mechanical properties of porcelain bodies have been studied extensively for almost a century. During this period three theories have been presented to explain the strength of porcelains.[1] These are the ''Mullite hypothesis'', the ''dispersion strengthening hypothesis'' and the ''Matrix reinforcement Hypothesis''.

The mullite hypothesis[2] suggests that porcelain strength solely depends on the felt-like interlocking of fine mullite needles. Specifically, the higher the mullite content and the higher the interlocking of the mullite needles, the higher is the bending strength.[3–6] Hence, the bending strength of porcelain depends on the factors that affect the amount and size of mullite needles like the firing temperature.[1]

On the other hand, the dispersion strengthening hypothesis[7] states that dispersed particles in the vitreous phase of a porcelain body, such as quartz and mullite crystals, in the glassy phase of a porcelain body limit the size of Griffith flaws resulting in increased strength.

Finally, the concept of the matrix reinforcement hypothesis concerns with the development of compressive stresses in the vitreous phase as a result of the different thermal expansion coefficients of dispersed particles or crystalline phases (usually quartz) and the surrounding vitreous phase. The larger these stresses are, the higher is the strength of the porcelain bodies.[1,8,9] The phenomenon is known as the pre-stressing effect.

Although, it is suggested that a universal theory of strength in porcelain bodies should account for all the above mechanisms of strengthening,[1] still there is an argument regarding the positive or negative effect of residual quartz on porcelain strength.

Specifically, mostly reports that support the mullite hypothesis or the dispersion strengthening hypothesis claim that the presence of residual quartz in fired bodies is harmful[10–12] to the porcelain strength due to the α-β transformation of quartz crystals during cooling.[4,5,10,13–16] It is reported that improved mechanical properties are observed by reducing quartz content[6,11,17] or by pulverizing quartz.[14–17] Additionally, higher strength can be obtained by the substitution of quartz by sillimanite sand,[10] alumina,[11,12,18] kyanite or mul-

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lite,[19] rice husk ash,[13] sericitic pyrophyllite[11] or low expansion porcelain powder.[20]

On the other hand, in accordance to the matrix reinforcement theory, there is abundant experimental evidence that under certain conditions residual quartz has a beneficial influence on porcelain strength,[1,5,8] It is reported that maximum bending strength is achieved by increasing residual quartz content and controlling quartz grain size in the range 10–30 μm.[5] Nevertheless, different views regarding the optimum conditions have also been expressed.[8,21]

Obviously there is a conflict between researchers for the positive or negative influence of quartz on porcelain strength, which is attributed to the many parameters that interfere. A simultaneous investigation of parameters such as quartz content, quartz grain size, firing temperature and soaking time would help in the direction of understanding the mechanisms controlling porcelain's strength and improving its mechanical properties. However, the enormous amount of experiments required for such an investigation limit researchers in studying one or two factors at a time (e.g. temperature and quartz content or temperature and quartz grain size).

The present work, which is a part of an extended research program, aims to elucidate the complex phenomena affecting porcelain strength development. In this respect four parameters were simultaneously investigated, in order to study their effect on mechanical and physical properties of a sanitaryware porcelain. To overcome the enormous amount of experiments, thus, saving time and resources required, the Taguchi approach for experimental design was employed. The values used for the four parameters lie in the range applied in industrial practice, in order to avoid or to limit an over-evaluation of the influence of any parameter (e.g. temperature by overfiring or underfiring). Subsequently, the objective is to determine the conditions under which, improved mechanical strength can be achieved compared to industrially produced sanitaryware porcelain. Finally, the results are discussed in respect to the three suggested theories considering the effect of quartz on the mechanical properties of porcelain.

2. Experimental procedure

2.1. Experimental design

The four investigated parameters were filler grain size, quartz content in filler, sintering temperature and firing time.

Three levels of values for each parameter were applied shown in Table 1 within the range usually used in industrial practice for the production of sanitary-ware porcelain.

In a full factorial experimental design all possible combinations of the factors should be tested. When the number of factors and the number of their distinct values (levels) are large, then the amount of experiments becomes impractical.[22] In this case by introducing four parameters at three levels each, the number of the required experiments for a full factorial analysis rises to $3^4 = 81$.

Aiming to reduce the number of experiments, namely to save time and resources, a fractional factorial design such as the Taguchi method can be used limiting the investigation to a specific subset of the full factorial experimental array.[22,23] In the present work, a four by nine experimental matrix, according to the Taguchi experimental design, was used. This array, referred in literature[22,24] as the L9 (3^4) Orthogonal Array, is presented in Table 2.

2.2. Materials and sample preparation

The required particle size distributions (PSD) of the filler (quartz and fired porcelain powders) were obtained by wet milling and separation of the desirable fractions by sedimentation (Table 3). Consequently, nine different slips were prepared. Their composition was: 28% Kaolin, 24% Ball clay, 19% Nepheline syenite, 13–29% quartz (content depends on the run as shown in Table 2) and 0–16% fired porcelain (content also depends on the run). The total amount of filler (quartz and fired porcelain) was kept constant at 29%.

After 24 h of slip ageing, 20 rods of 12 mm in diameter and 140 mm in length were prepared for each run by slip casting. Specimens were dried at 110 °C and then fired to the desired temperature as listed in Table 2. During firing, the temperature increasing rate was 120 °C/h up to 1000 °C and 180 °C/h from 1000 °C to the desired temperature. The furnace was left free to cool to room temperature. During cooling the rate was less than 1 °C/min below 800 °C.

2.3. Samples characterization

Open porosity and total porosity were determined after firing, by means of mercury porosimetry (Quantachrome Autoscan 33) and gas pycnometry. The bending strength for the 20 specimens of each run was measured using a 3-point loading method with a span of 100 mm and a crosshead speed of 1mm/min (INSTRON 8562).

Table 1
Values of each level for the factors studied

Factors	Level 1	Level 2	Level 3
A: Filler PSD	<5 μm	5–20 μm	20–40 μm
B: Quartz content	13%	21%	29%
C: Sintering temperature	1175 °C	1200 °C	1230 °C
D: Firing time	5 min	60 min	120 min

Table 2
Experimental conditions, L9 (3^4) orthogonal array

	FACTORS					
	Filler grain size (μm)		Filler content (%)		Firing temperature (°C)	Firing time (min)
RUN	SiO_2	Porcelain	SiO_2	Porcelain		
R1	<5	<5	29	0	1175	5
R2	<5	<5	21	8	1200	60
R3	<5	<5	13	16	1230	120
R4	5–20	5–20	29	0	1200	120
R5	5–20	5–20	21	8	1230	5
R6	5–20	5–20	13	16	1175	60
R7	20–40	20–40	29	0	1230	60
R8	20–40	20–40	21	8	1175	120
R9	20–40	20–40	13	16	1200	5

Table 3
Particle size distribution of quartz and porcelain powders

	Quartz powder			Porcelain powder		
	<5	5–20	20–40	<5	5–20	20–40
d_{10}	1.2 μm	6.3 μm	17.1 μm	1.1 μm	4.1 μm	16.2 μm
d_{50}	2.4 μm	11.4 μm	28.9 μm	2.1 μm	11.6 μm	23.9 μm
d_{90}	4.3 μm	18.9 μm	45.3 μm	3.6 μm	21.3 μm	41.1 μm

Crystal phase identification was performed by X-ray diffraction using a SIEMENS D500 diffractometer and quantitave analysis of the crystal phases was carried out by using metallic silicon as internal standard. The same internal standard was used in order to calculate the lattice parameter d_{211} of residual quartz and determine the induced stresses to the vitreous phase. The microstructure of the fired bodies was studied by means of Scanning Electron Microscopy (SEM) using a JEOL JSM-6300 apparatus, both on etched and non-etched polished, perpendicular surfaces of the rods.

2.4. Statistical analysis

Data analysis and interpretation were performed applying ANOVA[24] (ANalysis Of VAriance). The effect of each factor on the examined properties is expressed as a contribution percentage of the total variation observed. Finally the confidence level for the test of significance was set to 75%.

3. Results and discussion

3.1. XRD studies

Crystalline phases dispersed in the vitreous phase are considered very important factors influencing the mechanical properties of porcelain bodies, since all the three main theories described above focus on the effect of crystalline phases in order to explain the mechanical properties of porcelain. Quartz and mullite are identified by X-ray diffraction in all samples, whereas traces of cristobalite are identified only in samples fired above 1200 °C containing fine grained (<5 μm) quartz (i.e. Runs 2 and 3).

Particularly, for the residual quartz content the effect of the four tested parameters is shown in Fig. 1. Filler PSD and quartz content in the batch are the most important parameters contributing 46 and 37% to the observed variation respectively. Residual quartz content decreases as filler PSD decreases indicating that fine quartz grains are more prone to dissolution than coarser grains (Figs. 2–4). Firing time and temperature contribute 11 and 6% to the observed variation. The relatively small effect of temperature on residual quartz content can be attributed to the fact that firing above 1200 °C (Fig. 2) has no significant effect on quartz dissolution. On the other hand increased soaking time leads to increased quartz dissolution and decreased residual quartz (Figs. 2–4).

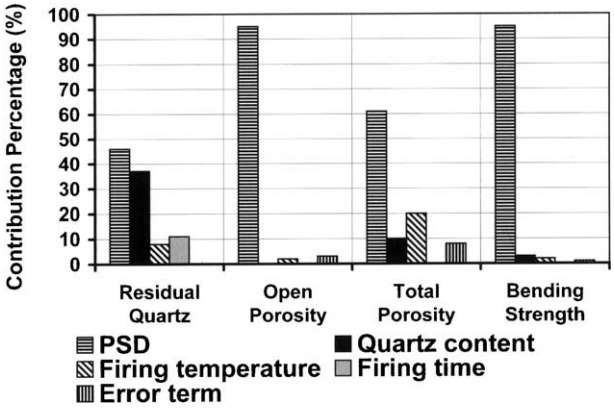


Fig. 1. Percent contribution of the studied factors on residual quartz content, open porosity, total porosity and bending strength.

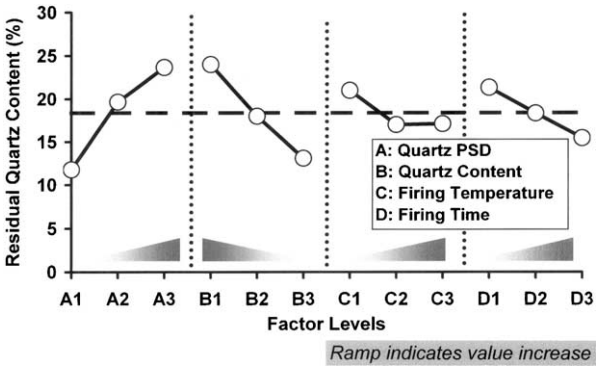
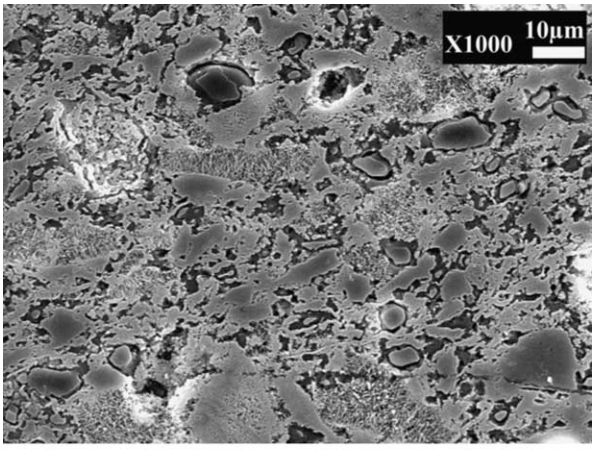


Fig. 2. Effect on the residual quartz content for the different levels of the studied factors.



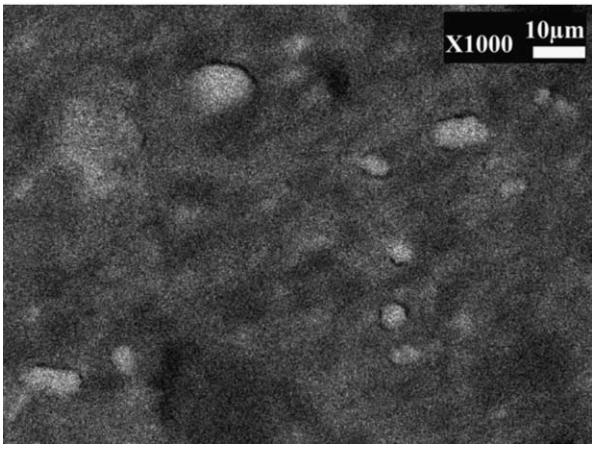
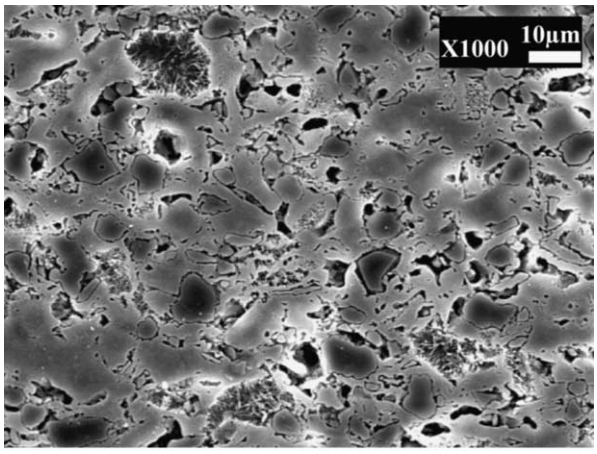


Fig. 3. SEM photographs of polished and etched cross section of a sample of Run 3 showing the un-dissolved quartz crystals.

3.2. Porosity and microstructure

Porosity and microstructure are considered important parameters regarding the mechanical properties of fired bodies[25] and therefore are going to be described in detail. Within the studied range of values for the four parameters, the factors that affect open porosity are filler PSD and firing temperature (Fig. 1). The former is the dominant factor by explaining 95% of the observed variation. Quartz content and firing time didn't pass the test of significance and, thus, they were ignored. The error term is very low, only 3%, indicating negligible experimental error and unexplained variation.



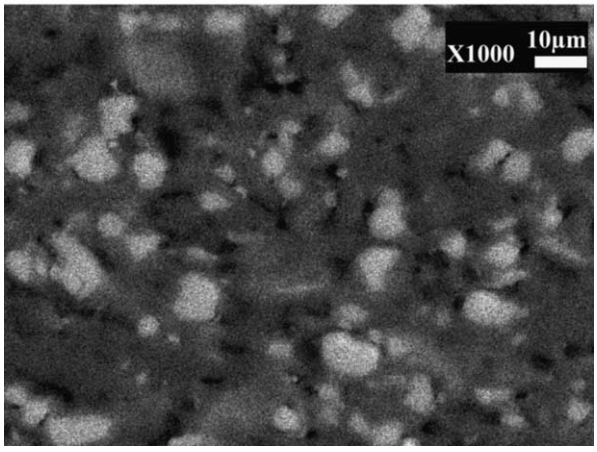


Fig. 4. SEM photographs of polished and etched cross section showing the un-dissolved quartz crystals in Run 6.

The statistically derived dominance of filler PSD on porosity is in line with the experimental observation that there is a significant increase in open porosity when 20–40 μm grain fractions are used (Fig. 5). Decreasing PSD to 5–20 μm, open porosity decreases significantly. Further porosity decrease is observed when fine grained filler is used. However, the difference in open porosity between 0 and 5 μm and 5–20 μm filler size fractions is considerably less pronounced compared to the difference between 5 and 20 μm and 20–40 μm fractions.

Contrary to the vast impact of filer PSD on open porosity, firing temperature has a small effect. Initially porosity decreases by increasing temperature (e.g. 1175–1200 °C), whereas, firing temperature above 1200 °C resulted in increase of the open porosity.

Similar trends are observed regarding the influence of the studied parameters on total porosity. Filler PSD is again the dominant factor explaining 61% of the

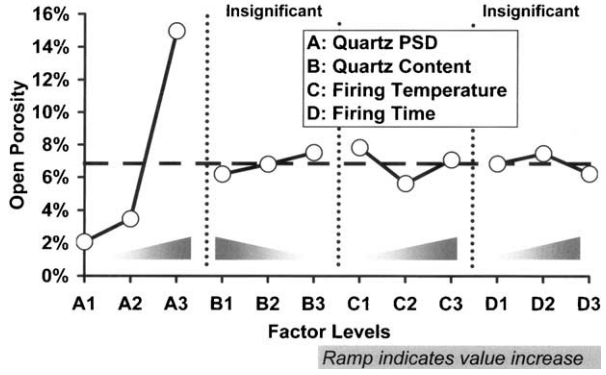


Fig. 5. Effect on the open porosity for the different levels of the studied factors.

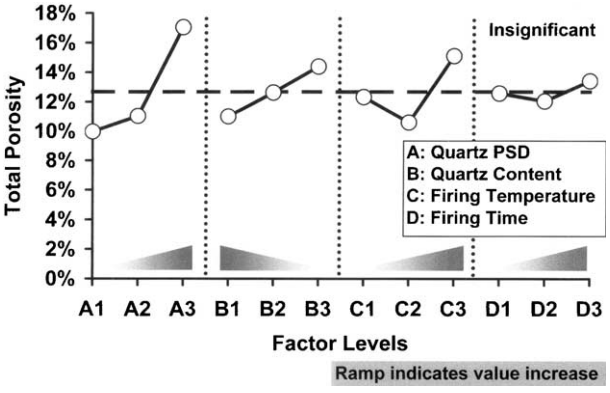


Fig. 6. Effect on the total porosity for the different levels of the studied factors.

observed variation, whereas the contribution of firing temperature and quartz content is 20% and 10% respectively (Fig. 1). Soaking time is ignored since it did not pass the test of significance.

Decreasing filler PSD leads to denser bodies (Fig. 6). The decrease in total porosity values is extensive if the filler PSD is reduced from 20–40 μm to 5–20 μm. Further decrease in filler PSD results in a slighter decrease of total porosity.

Comparing Figs. 5 and 6 it is evident that the effect of temperature on total porosity is analogous but more pronounced than its influence on open porosity. Total porosity initially decreases with increasing firing temperature. However, firing above 1200 °C results in higher total porosity probably due to bloating. This will be discussed later, in microstructure observations.

Table 4 suggests that the studied parameters do not only affect total porosity of the fired bodies but also the pore characteristics and the microstructure. In more detail, samples that contain fine grained filler (<5 μm) generally show few, isolated, spherical pores indicating that sintering is at the late stage. The diameter (∅) of the pores is in the range of 5–20 μm (Fig. 7a). Samples of Run 3, however, sporadically present larger pores in the range of ∅50–70 μm (Fig. 7b). Considering the fact that Run 3 was fired at the maximum tested temperature and time (1230 °C, 2h), the presence of such large pores associated with the high value of total porosity and the low value of open porosity indicates bloating.

In contrast, specimens in 20–40 μm sized quartz fractions (Runs 7 to 9 of Table 4) are not well sintered, as they are characterized by a large number of pores excessively interconnected (Fig. 7c). The shape of the pores is irregular and their size is between ∅5 and 40 μm.

Finally, samples containing filler in the range of 5–20 μm (Runs 4 to 6 of Table 4) present an intermediate microstructure. Specifically, the samples of Run 4 are characterized by small pores ∅5–15 μm, which are isolated and spherical (Fig. 7d). On the other hand, Run 5 and Run 6 present a larger number of pores than Run 4 (Fig. 7e). Additionally, the pores are less spherical (elongated or ellipsoid) and, especially, for Run 5 occasionally interconnected. The diameter of the pores is between 5 and 20 μm.

3.3. Bending strength

The effects of the four parameters on bending strength are shown in Fig. 1. Under the studied conditions the most important factor is filler PSD by explaining 95% of the observed variation. On the other hand, the variation in the results caused by firing

Table 4
Porosity, pore characteristics and bending strength of the fired bodies

RUN	Total porosity (%)	Open porosity (%)	Pore shape, size (μm)	Connected pores	Bending strength (MPa)
R1	7.9	2.4	Spherical, 5–20	NO	66.74
R2	7.2	1.4	Spherical, 5–20 (occasionally 30–50)	NO	63.00
R3	14.8	2.4	Spherical, 5–20 (occasionally 50–70)	NO	56.29
R4	8.0	1.0	Spherical, 5–15	NO	89.63
R5	13.3	3.7	Spherical-elongated 5–20	Occasionally	84.60
R6	11.8	5.8	Spherical-elongated 5–20	NO	83.36
R7	17.2	15.2	Irregular, 5–40	Excessively	53.59
R8	17.4	15.3	Irregular, 5–40	Excessively	56.37
R9	16.6	14.4	Irregular, 5–40	Excessively	52.95

temperature is minimal. The same holds true regarding the influence of quartz content in the filler, which is only 3%. This means that replacing part of the quartz in the batch by fired porcelain powder of the same PSD does not have a significant effect on bending strength. Thus, the observation reported by Masson,[20] namely, the substitution of quartz by fired porcelain powder has a significant and favorable result on the mechanical properties of porcelain bodies can not be confirmed. On the contrary, a slight increase of bending strength by increasing quartz content is observed (Fig. 8).

Finally, the fourth studied parameter, firing time, did not pass the test of significance and is considered unimportant.

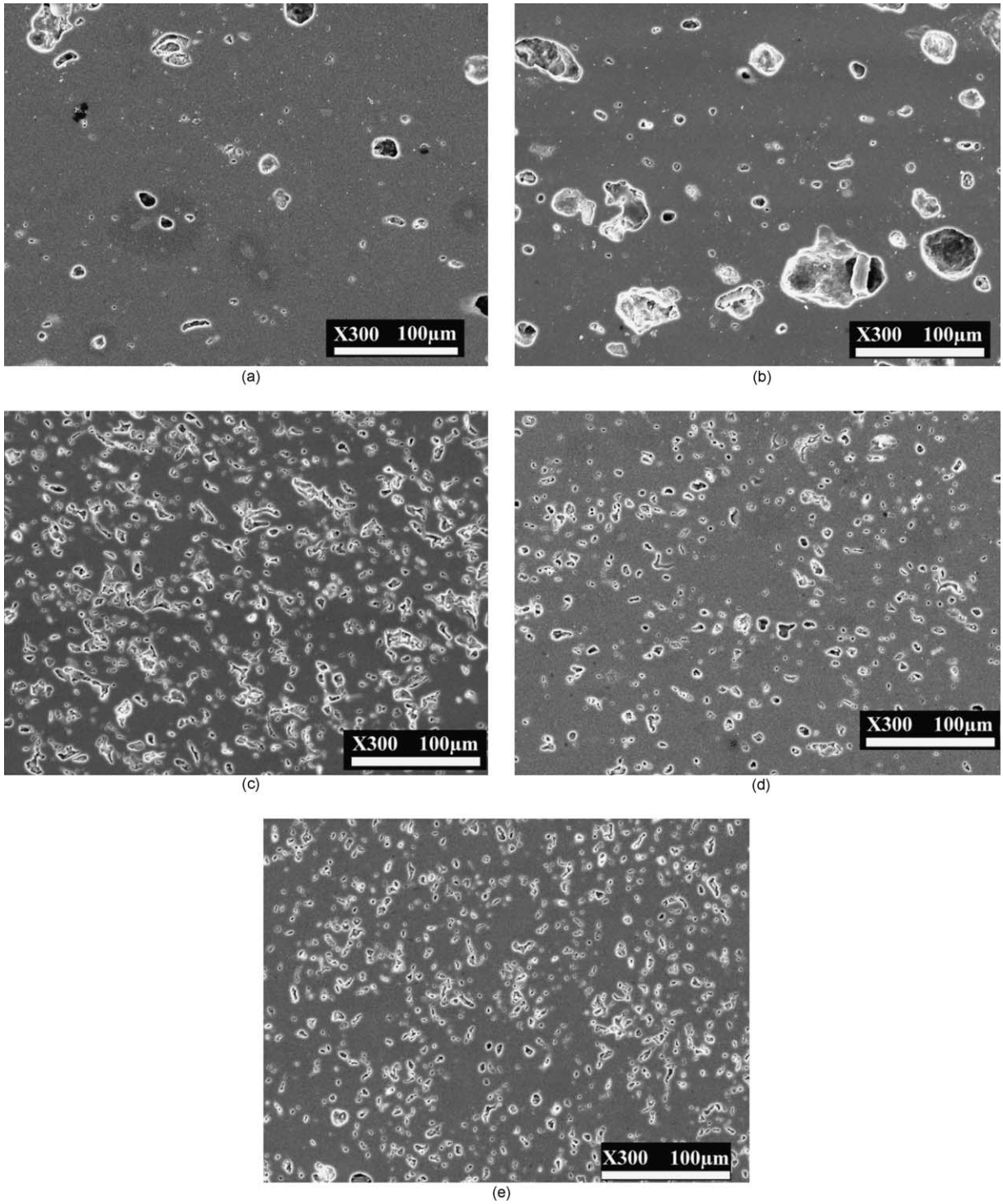


Fig. 7. SEM photographs of polished cross sections of fired bodies showing the pore characteristics of specimens containing different levels of filler PSD (a) <5 μm (Run 1), (b) <5 μm (Run 3), (c) 20–40 μm (Run 7), (d) 5–20 μm (Run 4) and (e) 5–20 μm (Run 4).

Obviously, the effect of filler PSD overwhelms the effect of the other three factors and dominates the mechanical properties of the fired bodies. The dominance of filler PSD is attributed to the large increase in bending strength observed for the fraction 5–20 μm of filler grains (Fig. 8). Finer or coarser grain fractions cause significantly lower bending strength values (30–40 MPa). These results are in agreement with the suggestion of the researchers[5,8,26] that there is an optimum quartz PSD which gives the highest bending strength. On the contrary, the observation of Mortel[14,16] is not testified, namely that increased mechanical properties are obtained if no quartz grains are present.

However, before reaching any conclusions concerning the mechanisms related to the existence of an optimum PSD, the relationship between bending strength, total porosity and microstructural characteristics must be examined. Additionally, it must be checked whether and how these results can be explained in respect to the three proposed theories.

3.4. Bending strength vs. total porosity and microstructure

Fig. 9 shows the relationship between the bending strength of the nine runs and their total porosity. Generally, bending strength in ceramics decreases exponentially by increasing porosity, and the denser the fired bodies are the higher the bending strength is.[25,27,28] Accordingly, the high total porosity of specimens that contain 20–40 μm filler grains accounts for the low bending strength values (Fig. 9). In contrast, despite the larger total porosity, samples of Runs 5 and 6 deviate from the above general rule exhibiting considerably higher bending strength than Runs 1 and 2 (Fig. 9). Additionally, the bending strength of Run 4 is significantly higher than the bending strength of Runs 1 and 2 even though these runs have the same total porosity. Thus, a sharp and clear relation between bending strength and total porosity can not be confirmed. However, if the results are divided into groups by grain size it is evident that bending strength decreases as the total porosity is meaningfully decreased.

It is reported[25,29] that interconnecting pores act as large fracture flaws reducing bending strength and that spherical, uniformly distributed pores less than 20 μm have a positive effect on bending strength. The low bending strength of the samples that contain 20–40 μm sized filler grains can be attributed not only to the high porosity but predominantly to the microstructure that is characterized by relatively large pores excessively linked to each other (Fig. 7c). Furthermore, the low bending strength of Run 3 compared to the bending strength of Runs 1 and 2 can also be attributed to the detrimental microstructure developed, which is characterized by the occasional presence of large (50–70 μm) pores. On the other hand, microstructure does not justify the large difference in bending strength observed between samples that exhibit the lowest values (~8%) of total porosity (Runs 1,2 and 4). The specimens of these Runs present spherical, non-connected pores less than ∅20 μm (Fig. 7a,d). Nevertheless, the mean bending strength is 67 and 63 MPa for Run 1 and Run 2, respectively, whereas for Run 4 is about 30% higher, namely 89 MPa. Furthermore, Run 5 exhibits significantly higher bending strength than Runs 1 and 2 despite the higher porosity and the sporadically connected pores. Consequently, the effect of microstructure on bending strength is detrimental and critical if it is characterized by excessively interconnected pores and high total porosity (poor sintering). On the other hand, microstructure and total porosity are not the key factors determining the bending strength of relatively dense bodies that present mostly small, isolated pores.

3.5. Bending strength versus the three proposed theories

In order to explain the differences in the mechanical properties which can not be explained by microstructure and total porosity, the relationship between bending

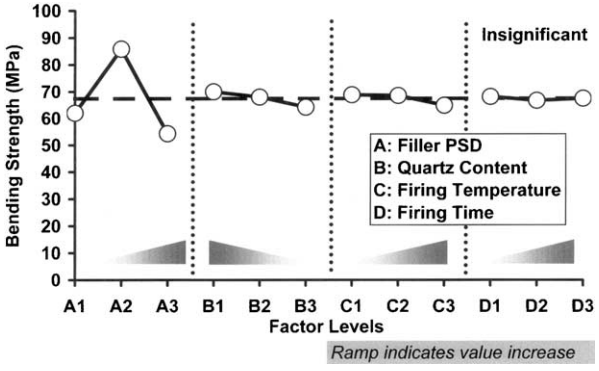


Fig. 8. Effect on the bending strength for the different levels of the studied factors.

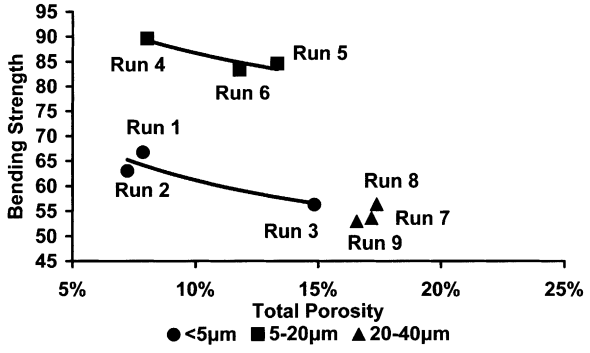


Fig. 9. Relation between bending strength and total porosity of fired bodies.

strength and the following three parameters is examined: Stresses induced to the vitreous phase (pre-stressing effect), Mullite content and Quartz residue.

The stresses induced to the vitreous phase are determined by calculating the lattice parameter d_{211} of residual quartz. The normal value (stress free) for d_{211} is 1.541Å. Higher values of d_{211} indicate that quartz particles are under tensile stresses and the vitreous phase under compressive stresses.[8] The relation of mean bending strength values and the lattice distances of residual quartz crystals in the samples is presented in Fig. 10. It is observed that bending strength increases as the d_{211} value increases and that the maximum bending strength is obtained at ~1546Å. The high bending strength of the samples that contain 5–20 μm quartz grains (Runs 4, 5 and 6) which can not be explained in terms of microstructural characteristics and total porosity may be attributed to the high compressive stresses induced to the vitreous phase (Fig. 10). Indeed, the observed increase of bending strength with the increase of the compressive stresses induced to the vitreous phase is consistent with the matrix reinforcement theory.

On the other hand the beneficial influence of mullite content on bending strength is not evident (Fig. 11), since none relationship between mullite content and bending strength could be identified. Therefore, the high bending strength of Runs 4, 5 and 6 can not be explained in relation to the mullite content.

Finally, according to the dispersion strengthening hypothesis increased residual quartz content results in higher bending strength due to the presence of more dispersed particles in the vitreous phase.[10] However, a clear relationship between residual quartz content and bending strength is not observed (Fig. 12). Although, a decrease in the bending strength for the samples containing 0–5 μm sized filler grains is evident the high bending strength of samples containing 5–20 μm quartz grains can not be explained in terms of the residual quartz content.

3.6. Final considerations

As described earlier filler PSD dominates porcelain strength and this fact is attributed to the high bending strength of samples containing 5–20 μm filler grains (Runs 4, 5 and 6). This result can now be further explained and analyzed. It was found that in order to obtain high mechanical properties three conditions must be fulfilled, namely the relatively low total porosity, the presence of small and mostly isolated pores and the high pre-stressing effect. It was also observed that in the range of values studied these three conditions are controlled by quartz PSD (Figs. 6 and 10, Table 4). Using coarse filler (20–40 μm) sintering is retarded leading to high porosity (~17%) and relatively large interconnected pores. These interconnected pores act as large fracture flaws significantly lowering the mechanical properties. Using finer filler sintering enhances, porosity decreases and bending strength increases with the transition of pores from excessively interconnected and irregular to isolated and spherical.

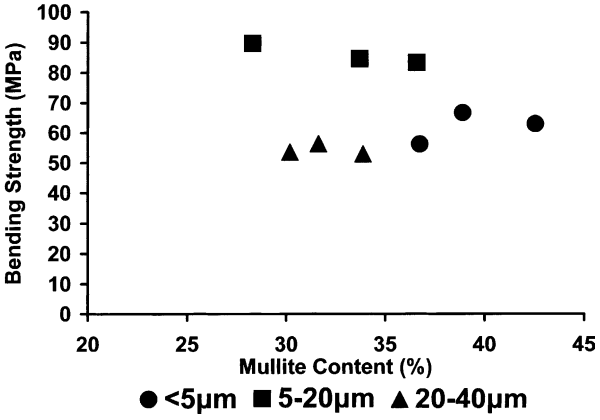


Fig. 11. Relation between bending strength and mullite content in fired bodies.

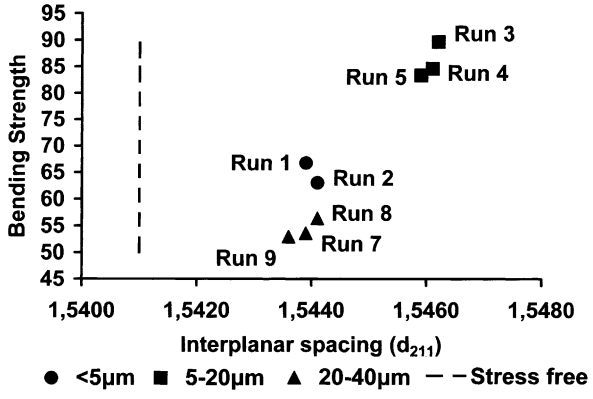


Fig. 10. Relation between bending strength and lattice parameter d_{211} of quartz in fired bodies.

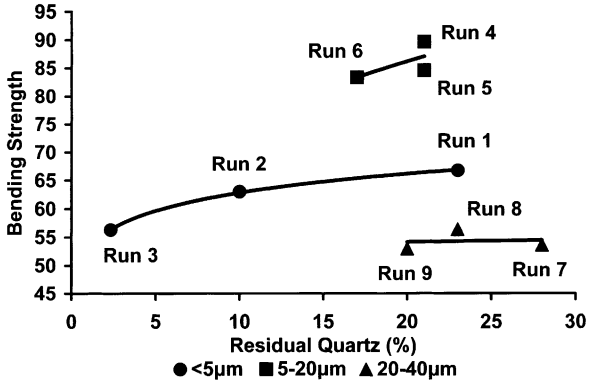


Fig. 12. Relation between bending strength and residual quartz content in fired bodies.

Table 5
Comparison between reference porcelain and Runs 4 and 5

	Firing conditions (temperature/time)	Bending strength
RUN 4	1200 °C/2 h	89.6 MPa
Reference	1200 °C/2 h	75.5 MPa
RUN 5	1230 °C/5 min	84.6 MPa
Reference	1230 °C/5 min	65.7 MPa

The beneficial effect of the induced stresses on bending strength becomes apparent when the microstructure is not detrimental for the mechanical properties. In the present work non-detrimental microstructure is observed for 0–5 μm and 5–20 μm quartz grains (Runs 1, 2 and 3–6 respectively). The later size fraction induced higher compressive stresses to the vitreous phase leading to large increase of bending strength. Thus, it can be concluded that quartz grain size dominates strength in two ways. Directly by inducing compressive stresses to the vitreous phase and indirectly through the development of a favorable microstructure for the mechanical properties. Consequently, optimization efforts should be focused on quartz PSD, since in the narrow range of values tested quartz content, sintering temperature and firing time have a minimal effect on bending strength. The optimum grain size range found to be 5–20 μm which is higher than the reported[8] 0–5 μm when maturing temperature is ~1200 °C. Bearing in mind that the optimum grain size found is considerably lower than the filler grain size used in industrial practice for the production of sanitaryware porcelain (typically <63 μm)[1] a significant improvement of the mechanical properties should be expected by controlling filler PSD below 20 μm. Indeed, 20–30% higher bending strength is observed by using filler PSD in the range 5–20 μm (Runs 4 and 5) compared to the reference porcelain (Table 5).

4. Conclusions

In the narrow range of values used by industrial practice filler grain size has severe impact on the mechanical and physical properties of porcelain compared to the impact of the other three factors, namely quartz content in the filler, firing temperature and soaking time that were tested. Thus, optimization efforts should be focused on this factor.

Bending strength is affected by quartz grain size in two ways, directly through the induction of compressive stresses to the vitreous phase and indirectly through the development of a favorable microstructure. Both these parameters depend strongly on the PSD of quartz grains. The optimum quartz grain size is 5–20 μm which gives the maximum bending strength. The use of coarser grain sizes results in reduced bending strength due to the development of a detrimental microstructure for the mechanical properties. The microstructure is very porous and characterized by large, irregular pores connected to each other. On the other hand, using finer quartz grains results in low bending strength due to limited pre-stressing effect. Controlling quartz grain size in the optimum range bending strength is increased by 20–30% compared to the reference porcelain.

The results are consistent with the matrix reinforcement theory. However, the beneficial influence of mullite content on bending strength is not confirmed. In addition, replacing part of quartz content with fired porcelain did not result in a positive effect on bending strength.

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References

1. Carty, W. M. and Senapati, U., Porcelain-raw materials, processing, phase evolution, and mechanical behaviour. *J. Am. Ceram. Soc.*, 1998, **81**(1), 3–20.
2. Zoellner, A., Zur Frage der chemischem und physikalischen Natur der Porzellans. *Sprechsaal*, 1908, **41**, 471–473.
3. Sane, S. C. and Cook, R. L., Effect of grinding and firing treatment on the crystalline and glass content and the physical properties of Whiteware bodies. *J. Am. Ceram. Soc.*, 1951, **34**(5), 145–151.
4. Schroeder, J. E., Inexpensive high-strength electrical porcelain. *Am. Ceram. Soc. Bull.*, 1951, **57**, 526.
5. Mattyasovsky-Zsolnay, L., Mechanical strength of porcelain. *J. Am. Ceram. Soc.*, 1957, **40**(9), 299–306.
6. Palatzky, A. and Werner, T., Increasing the mechanical strength of porcelain bodies. *Silikat. Tech.*, 1958, **9**, 68–73.
7. Hasselman, D. P. and Fulrath, R. M., Proposed fracture theory of a dispersion strengthened glass matrix. *J. Am. Cer. Soc.*, 1966, **49**(2), 68–72.
8. Hamano, K., Wu, Y.-H., Nakagawa, Z. and Hasegawa, M., Effect of grain size of quartz on mechanical strength of porcelain bodies. *J. Ceram. Soc. Jap. Int.*, 1991, **99**, 149–153.
9. Tomizaki, M. F. and Sugiyama, T., Study on high silica porcelain bodies (effects of siliceous stone grain size). *Interceram.*, 1995, **44**(4), 223–228.
10. Maity, S. and Sarkar, B. K., Development of high strength Whiteware bodies. *J. Eur. Ceram. Soc.*, 1996, **16**, 1083–1088.
11. Prasad, C. S., Maity, K. N. and Venugopal, R., Replacement of quartz and potash feldspar with sericitic pyrophyllite in Whiteware compositions. *Interceram.*, 1991, **40**(2), 94–98.
12. Warshaw, S. I. and Seider, R., Comparison of strength of triaxial porcelains containing alumina and silica. *J. Am. Ceram. Soc.*, 1967, **50**(7), 337–348.
13. Prasad, C. S., Maity, K. N. and Venugopal, R., Effect of rice husk ash in Whiteware compositions. *Ceram. Int.*, 2001, **27**, 629–635.
14. Mortel, H., Einfluss der Verfahrensparameter auf die Eigenschaften von Schnellbrandporcellan. *Keramische Zeitschrift*, 1978, **30**(9), 479–482.

15. Mortel, H., Influencing of the processing parameters on the properties of rapid fired porcelain., *Proc. 14th Univ. Conf. on Ceramic Sci. 'Processing of Crystalline Ceramics' held at North Carolina State University, Raleigh, November, 7–9, 1977*.
16. Mortel, H., Influence of the batch composition on the reaction behaviour and properties of fast-fired (2 h) porcelain. *Science of Ceramics*, 1977, **9**, 84–91.
17. Weyl, D., Uber den Einfluss innerer Spannungen auf das Gefuge und die mechanische Festigkeit des Porcelans. *Ber. Deutsc. Keram Gesel*., 1959, **36**, 319–324.
18. Khandelwal, S. K. and Cook, R. L., Effect of alumina additions on crystalline constituents and fired properties of electrical porcelains. *Am. Ceram. Soc. Bull*., 1970, **49**(5), 522–526.
19. Leonelli, C., Bondioli, F., Veronesi, P., Romagnoli, M., Manfredini, T., Pellacani, G. C. and Cannilo, V., Enhancing the mechanical properties of porcelain stoneware tiles: a microstuctural approach. *J. Eur. Ceram. Soc*., 2001, **21**, 785–793.
20. Masson, R., Gefugespannungen und Zugfestigkeit von Hartporzellan. *Keramische Zeitschrift*, 1957, **9**(3), 110–112.
21. Kobayashi, Y., Ohira, O., Satoh, T. and Kato, E., Effect of quartz on the sintering and bending strength of the porcelain bodies in quartz-feldspar-kaolin system. *J. Ceram. Soc. Jap. Int. ed*., 1994, **102**, 100–105.
22. Weiser, M. W. and Fong, K. B., Experimental design for improved ceramic processing, emphasizing the Taguchi method. *Am. Ceram. Soc. Bul*., 1993, **72**(12), 87–92.
23. Weiser, M. W. and Fong, K. B., Application of the Taguchi method of Experimental design to improving ceramic processing. *Am. Ceram. Soc. Bull*., 1994, **73**(1), 83–86.
24. Roy, R. K., *Design of experiments using the Taguchi approach*. John Wiley & Sons, New York, 2001.
25. Kobayashi, Y., Ohira, O. and Kato, E., Effect of firing temperature on bending strength of porcelains for tableware. *J. Am. Ceram. Soc*., 1992, **75**(7), 1801–1806.
26. Marzahl, H., Influence of quartz on the strength of porcelain. *Ber. Deut. Keram. Ges*., 1955, **32**(7), 203–211.
27. Hamano, K. and Hirayama, M., Effect of quartz addition on mechanical strength of porcelain bodies prepared from pottery stone. *J. Ceram. Soc. Jap. Int. Ed*., 1994, **102**, 664–668.
28. Dinsdale, A. and Wilkinson, W. T., Strength of Whiteware bodies. *Proceedings of the British Ceramic Society*, 6, 119-136.
29. Ece, O. I. and Nakagawa, Z., Bending strength of porcelains. *Ceram. Int*., 2002, **28**, 131–140.