The influence of yttria-stabilised zirconia and cerium oxide on the microstructural morphology and properties of a mica glass-ceramic for restorative dental materials

Thapanee Srichumpon1, Supahud Pintasiri1, Greg Heness2, Cristina Leonelli2, Ekarat Meechoowas2, Noparat Thongpun2, Chayada Teanchai3, Kallaya Suputtamongkol4 and Duangrudee Chaysuwan1

1Department of Materials Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand; 2Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Modena, Italy; 3Department of Science Service, Ministry of Higher Education, Science, Research and Innovation, Bangkok, Thailand; 4Department of Prosthodontics, Faculty of Dentistry, Mahidol University, Bangkok, Thailand

ABSTRACT
The addition of yttria-stabilized zirconia and cerium oxide to this mica glass ceramic was found to increase mechanical properties and decrease chemical solubility. They were also found to be able to control translucency. X-ray diffraction showed no significant change in phase formation with phlogopite-Ca mica, fluorapatite and tetragonal zirconia the main phases present with their addition. Scanning electron microscopy showed that the additives did affect the grain morphology significantly and this was the controlling factor in the observed changes in strength, hardness, and solubility. The microstructures consisted of mainly plate-like and interlocking crystals. The largest increased in strength and hardness and the largest decreased in chemical solubility can be attributed to the largest change in grain morphology by the addition of both the YSZ and CeO2. The values of hardness, biaxial flexural strength and chemical solubility were 3.5–6.2 GPa, 105–120 MPa and 142–732 μg/cm², respectively making them acceptable for dental materials according to ISO 6872-2015. The addition of YSZ increased the opacity, whilst the CeO2 improved translucency and influenced the color to a yellowish to yellow-brownish shade close to Thais’ teeth.

1. Introduction
All ceramics for dental restoration must have excellent mechanical properties and a color and translucency close to that of natural teeth. The original color of glass-ceramics is white, so it must be adjusted to match that of natural teeth. Mica glass-ceramic is used as a restorative dental material because it has good biocompatibility and machinability [1,2], which allows fabrication by computer numerical control (CNC) in conjunction with computer-aided design/computer-aided manufacturing (CAD/CAM) systems [3]. Despite these admirable properties it cannot be used for a variety of applications in dentistry because of its relatively low strength. Phlogopite mica glass-ceramic is known under the commercial trademark MACOR [4]. There are several strategies to improve the strength of these mica glass-ceramics including the use of zirconia (ZrO2) [5]. The addition of yttria-stabilized zirconia (YSZ) results in better mechanical properties, such as hardness, elastic modulus, brittleness index, chemical solubility [6–8] as well as a higher degree of machinability [9]. However, ZrO2 has the drawback of low translucency and a milky-white color [10]. Therefore, the addition of coloring agents to match a patient’s original teeth is essential. Pigment additives or metal ions such as iron (Fe), cerium (Ce) and praseodymium (Pr) are used for brownish, yellowish-brown and dark yellowish colors, respectively [11]. Moreover, zircon-based pigments have been extensively applied in the industry because they are color stable under high firing temperatures [12,13]. Examples are praseodymium zircon yellow (Pr-ZrSiO4), ferrum zircon red (Fe-ZrSiO4), and vanadium zircon blue (V-ZrSiO4) [14,15]. The addition of CeO2 increases the yellow hues [16], providing a promising candidate for denture replacement materials [17]. The purpose of this study is to investigate the effect of YSZ and CeO2 addition on the optical properties, chemical composition, microstructural morphology, mechanical properties, and chemical solubility of the mica glass-ceramics.

2. Material and methods
2.1. Preparation of glass-ceramics
Mica glass-ceramics were prepared from a glass frit feedstock of 37%SiO2, 15.9%MgO, 13.6%SrCO3, 11.9%Al2O3, 6.5%CaCO3, 3.0%P2O5, and 0.6%CaF2 as. The glass frit was ground to less than 45 μm. Cerium oxide (< 5 μm) and/or YSZ (10–15 nm) were added according to the ratios in Table 1. All chemicals were

CONTACT Duangrudee Chaysuwan  fengddc@ku.ac.th  Department of Materials Engineering, Faculty of Engineering, Kasetsart University, Bangkok,10900, Thailand

© 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group on behalf of The Korean Ceramic Society and The Ceramic Society of Japan. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
homogeneously mixed, in a rolling mill for 2 h. They were melted in a furnace at 1450°C while another furnace was used to heat a carbon mold to the annealing temperature at 582°C for 90 min. The melted glass was poured into a 16 mm diameter by 115 mm long cavity in the heated carbon mold followed by annealing to relieve thermal stresses in the glass rod. The glass rod was then heat-treated in two stages: nucleation at 643°C for 10 min followed by crystallization at 897°C for 10 min both with a 55°C/min heating rate, to transform the glass to glass-ceramics. The heat treatment temperatures were those used in a previous work on these materials [18] and were calculated according to Marotta’s regime [19].

### 2.2. Characterization

Phase transformation was examined at room temperature by X-ray diffraction (XRD; X’pert PW 3040/00, Phillips, Netherlands) which each sample, sliced from the cast rod, scanned from 5° 2θ to 80° 2θ with a step size of 0.05° 2θ and a count time of 2 s at 30 kV and 40 mA. All specimens were progressively ground from 600 to 2500 grit with silicon carbide abrasive paper and then polished with 0.1 μm alumina paste and etched by 10% hydrofluoric acid solution for 15 sec. The etched specimens were cleaned and sputtered with gold. The percent crystallinity and aspect ratio of the crystalline glass-ceramics were observed by scanning electron microscope (SEM, JSM-7800 F, JEOL Ltd, Japan) and calculated by the ImageJ/Fiji software [20] by area. The crystalline phase was identified by X-ray analysis in a 20 range of 5° to 40° with a Bragg-Brentano system. The X-ray data were collected using a generator (Phillips, Almelo, The Netherlands) operated at 40 kV and 100 mA. The X-ray diffraction patterns were recorded using Cu Kα radiation (λ = 0.1541 nm) with a scanning rate of 0.02° sec−1. The crystallinity of the glass-ceramics was determined by the following equation:

\[
\text{Crystallinity} = \frac{A_{c}}{A_{c} + A_{g}} \times 100\%
\]

where \(A_{c}\) and \(A_{g}\) are the areas of the crystalline and glassy peaks, respectively.

The color properties were determined using a colorimeter (X-rite, Hunter Lab USA) with a 1° observer and D65 standard illuminant. The colorimeter was calibrated using a standard white ceramic tile. The color data were recorded as L*, a*, and b* values using the CIE L*a*b* color system. The color differences were calculated using the following equation:

\[
\Delta E = \sqrt{(L_{1} - L_{2})^2 + (a_{1} - a_{2})^2 + (b_{1} - b_{2})^2}
\]

where \(L_{1}\) and \(L_{2}\) are the lightness values of the two samples, and \(a_{1}\) and \(b_{1}\) are the chromaticity coordinates of the two samples.

### 3. Results and Discussion

#### 3.1. XRD analysis

The XRD patterns in Figure 1 identify the crystalline phases present in the glass-ceramics. The slight hump from approximately 20° to 35° 2θ suggest the presence of a residual glassy phase. For all samples, the following phases were identified: phlogopite (CaMg₆Al₂Si₄O₁₀F₂, JCPDS: 025-0155), anorthite (CaAl₂(SiO₄)₂, JCPDS: 00-002-0523), fluorapatite (Ca₅(PO₄)₃F, JCPDS: 00-060-0667), and the major phases are tetragonal zirconia (t-ZrO₂, JCPDS: 00-070-7300). Calcium magnesium silicate (CaMg₃(SiO₄)₂, JCPDS: 00-002-0455) is more prevalent in the
3.2. Microstructural analysis

The crystalline structure of the original glass-ceramic is shown in Figure 2 and the metrics for morphology are given in Table 2. The addition of the 1% ceria had little effect on the level of crystallinity in these glass-ceramics with only about a 4% increase. The effect on morphology is, however, more pronounced with a 23% decrease in length of the long axis and a 22% decrease in the short axis of the grains resulting in a decrease in the aspect ratio of 27% (Figure 2 (a2) and (b2)). As stated in the previous section CeO$_2$ can act as a nucleating agent in these glass ceramics and this is exhibited by the observed change in crystal morphology here. The addition of 5% YSZ had a dramatic effect, changing the crystal morphology from tabular to equiaxed with a 77% decrease, from the GC specimens, with the aspect ratio approaching 1 (Figure 2 (a3) and

Figure 1. XRD patterns of glass-ceramics crystallized at 897°C.

Figure 2. SEM micrographs of (a) the polished and etched surfaces (a1) GC, (a2) GCC, (a3) GCY and (a4) GCCY and (b) the fracture surface of the glass-ceramics (b1) GC, (b2) GCC, (b3) GCY and (b4) GCCY, 1000x.
(b3)). The addition of YSZ has been shown to slow the crystal growth kinetics in these glass ceramics slowing the cooling and allowing the growth of more equiaxed crystals. The addition of both 1% CeO to the specimens with 5% YSZ had, not surprisingly, the effect of a large decrease in the mica crystal size, from 36.5 μm in GCCY to 7.8 μm in GCCY, (≈80%) further, with no change in morphology (Figure 2 (a4) and (b4)).

The fracture surfaces revealed interlocking plate-like crystals with the crack path appearing to be mainly in the thin glassy phase. Some evidence of crystal fracture is observed. The difference in aspect ratios again observed in these fractographs with the GC and GCC materials showed large plate-like crystals with high aspect ratios while the GCC and GCCY low aspect ratios. The added YSZ particles can act as a most efficient nucleating agent to promote nucleation of mica crystals.

### 3.3. Optical properties

The color of a dental restorative material should have a yellow to the reddish-yellow gradient to be acceptable. Photographs, showing the difference in color and translucency, of the glass ceramics produced are shown in Figure 3. The translucency parameter indicates the reflected color difference, over white and black backgrounds, between materials with uniform thickness. It is considered to give the best measurement of human perception of translucency [30]. It is specified as one of the primary factors in controlling esthetics and used for the selection of materials for dental applications [31]. A high translucency parameter (TP) indicates that the material is less opaque. A material with a TP of 100 is considered transparent; a TP of 0 indicates that the material is opaque. In addition, the contrast ratio, another measure of translucency, was measured so as to compare results with the most recent literature [18]. The mean of contrast ratio and translucency parameter are reported in Table 2. After the heat treatment process, the color of the resulting glass-ceramic changed with the CeO₂ additions producing a yellowish hue [32] and the addition of YSZ producing a whiter material [17,33] (Figure 3).

The addition of YSZ also caused a higher opacity [34,35], especially without CeO₂ additions. The general transparency and opacity are influenced by the number and/or grain size of crystals [36]. For the GCC and GCCY specimens the addition of YSZ and CeO₂ had the effect of slightly decreasing the contrast ratio for the former and slightly increasing it for the latter. Comparison of Tables 2 and 3, as well as reference to Figure 3, can help explain the observed effects on the optical properties measured. The addition of CeO₂ (GC-GCC) to the glass ceramics caused a decrease in average crystal size with a concomitant increase in translucency (a decrease in the contrast ratio and an increase in the translucency parameter). Many studies have described how a smaller mean grain size has led to an enhanced translucency [37–39]. The addition of CeO₂ has been found to improve translucency giving a higher translucency parameter [40].

With the addition of YSZ to the base GC, a small decrease in average grain size might expect no significant difference in translucency, which is the case here, see Figure 3 where there is little difference in opacity, though the GCCY specimens appears whiter. If ZrO₂ is used as a nucleating agent it forms a whiter glass-ceramic after the heat-treatment process [17,33].

![Figure 3. Optical appearance for 1 mm thick glass-ceramics.](image-url)
Table 3. L*a*b*, contrast ratio and translucency of the glass-ceramics.

| Materials | ΔL*  | Δa*  | Δb*  | Contrast ratio | Translucency |
|-----------|------|------|------|----------------|--------------|
| GC        | −10.643 | −3.53 | −0.13 | 0.89 ± 0.00 | 0.40 ± 0.12 |
| GCC       | −5.67 | −4.08 | −6.83 | 0.75 ± 0.00 | 11.07 ± 0.09 |
| GCCY      | −9.67 | −3.87 | −0.28 | 0.04 ± 0.00 | 2.40 ± 0.27 |
| GGY       | −4.32 | −5.89 | −7.64 | 0.45 ± 0.01 | 12.87 ± 0.27 |

For the GCCY material there was a large decrease in grain size and shape. This, together with the addition of the CeO₂, resulted in a large increase in translucency over the GC and GCC materials. Altering the grains to a more uniform size and morphology and reducing the number and size of the porosity can lead to improvement in translucency [24]. A more moderate increase over the GCC materials is observed suggesting that the addition of CeO₂ has more of an impact on translucency than the grain size.

Regarding the contrast ratio, GCCY had the lowest value with a higher translucency than the other materials, as just discussed. Contrast ratios and translucency parameters are considered important variables for dental ceramics selection and are well-established parameters [27,41]. However, in the end, the color and translucency matching must be decided by the dentist and the patient in consultation. The contrast ratios, for 1 mm thick specimens, have values close to commercially available prosthetics [42]. Comparison of these materials to commercially available materials is important. Table 4 provides such a comparison. The GC material (0.89) is like nCoris AL (0.89), GCC (0.75) close to IPS e.max ZirCADv (0.78) and IPS e.max MO (0.71), GCCY (0.94) close to In-Ceram Zirconia (1.00) and GCCY (0.45) close to IPS e.max HT (0.48) (Table 4). For natural teeth, the contrast ratio of human enamel and dentine are 0.45 and 0.65, respectively [43] (Table 4). The translucency parameters also showed comparable values to that of commercial materials [44]; c.f. GCC (11.07) and GCCY (12.67) with In-Ceram IPS e.max ZirCAD (11.48) and Sirona InCoris Z1 (12.64). The mean translucency values of 1 mm thick human enamel and dentine are 18.7 and 16.4, respectively [45]. The combination of CeO₂ and YSZ (GCCY) shows a contrast ratio and a translucency parameter similar to those of human enamel and other commercially available materials. The GCCY material had the smallest crystal size as in Figure 2(b4), therefore, it exhibited more translucency and CeO₂ influenced the color of yellowish and yellow-brownish shades close to natural teeth.

Table 4. The contrast ratio was compared between materials in research with commercial materials and natural teeth.

| Materials | Contrast ratio | Commercial Materials [42] | Contrast ratio |
|-----------|----------------|----------------------------|----------------|
| GC        | 0.89           | In-Ceram Zirconia            | 1.00           | Dentine         | 0.65 |
| GCC       | 0.75           | nCoris AL                   | 0.89           | Enamel          | 0.45 |
| GCCY      | 0.94           | IPS e.max ZirCADv            | 0.78           | IPS e.max MO    | 0.71 |
| GCCY      | 0.45           | IPS e.max HT                | 0.48           | IPS e.max HT    | 0.48 |

3.4. Mechanical properties

The YSZ and CeO₂ additives caused an increase in strength and microhardness. For GC and GCC, the similar microstructures resulted in similar biaxial flexural strengths and hardness (Figure 4). The more pronounced change in crystal morphology discussed in section 3.2 resulted in a more pronounced effect on hardness with a smaller effect of strength. The propagation of a crack front depends on microstructural factors such as crystal size, crystal shape, the aspect ratio of the crystal and crystallinity [46]. As the per cent crystallinity is hardly affected, there would be little effect from this on the observed strengths. The fracture front in these materials tend to travel through the more brittle glassy phase between the crystals. Inspection of Figure 2(a) shows that the thickness of the glassy phase decreases slightly. The crystal size does decrease but not significantly. These two factors may suggest why no large increase in strength was observed even for the GCCY material where a large decrease in crystal size was observed. Higher aspect ratios for these glass ceramics has been found to cause lower strengths [47]. This is supported by the results given here.

Hardness was affected by the aspect ratio of the crystals, the crystallinity and spatial area of the grains [47]. Mica is a relatively soft crystal when compared to the glass. The indent size is comparable to the grain size for the GC and GCC materials, with a resultant little difference in hardness. With the change in morphology on the addition of the YSZ, hardness increased and for the GCCY materials a very large increase in hardness was observed. This is due to the closer spacing of the harder, glassy phase between the softer crystals causing more resistance to indent penetration. The much smaller crystals in the GCCY and GCCY specimens may also be harder simply due to their reduced size. The range of biaxial strengths and hardness were 105–120 MPa and 2.4–6.5 GPa. This makes them acceptable as restorative dental materials according to ISO 6872 Type 2 Class 1 and 2.

Table 5. Chemical solubility of glass-ceramics.

| Materials | Chemical solubility (μg/cm²) |
|-----------|-----------------------------|
| GC        | 732.37 ± 30.18              |
| GCC       | 674.30 ± 37.25              |
| GCCY      | 499.34 ± 38.74              |
| GGY       | 142.25 ± 20.88              |
Figure 5 show micro indentation cracking of the mica glass-ceramics. Inspection of Figure 5 shows that determination of the crack lengths for fracture toughness calculation is not possible. For the GCCY specimens, the cracks were able to be measured resulting in the determination of a fracture toughness of 2.7 MPa·m$^{1/2}$. This makes this material acceptable as restorative dental material according to ISO 6872 Type 2 Class 1 and 2.

3.5. Chemical solubility

In general, the amorphous phases are more soluble than the crystalline phases [48]. The actual crystalline phase will also affect solubility. Comparison of Tables 2 and 5 shows no clear correlation between the level of crystallinity and chemical solubility in the materials studied here. However, as stated previously, the thickness of the glassy phase reduced which may affect the access of the solvent. However, it should be considered that the crystalline phases present also contribute to controlling solubility in these glass-ceramics. A significant decrease in solubility was observed with the addition of the YSZ suggesting the lower chemical solubility may be attributed to the presence of the tetragonal zirconia phase which presents higher resistance to chemical solubility than the fluorapatite and other phases [7,18,34]. The GCCY material with the
lowest chemical solubility of 142–732 µg/cm², is acceptable as a dental material according to ISO 6872 Type 2 Class 2b [21].

4. Conclusions

The addition of YSZ and CeO₂ have affected the biaxial strength, hardness, optical and chemical properties of the glass ceramic used in this study. Their addition did not significantly affect the phases formed. In general, the addition of these materials increased mechanical properties and reduced chemical solubility. The largest increase was in mechanical properties and the largest decreased in solubility was from the combined addition. These changes can be attributed to the change in grain morphology introduced by the additives. Translucency was increased by the addition of YSZ and decreased by the addition of CeO₂ in line with other studies.

All the glass-ceramics developed here can be used as restorative dental materials according to ISO 6872 Type 2 Class 2b (partially or fully covered substructure ceramic for single-unit anterior or posterior prostheses adhesively cemented) [21]. This good combination of properties and esthetics made these mica ceramics great candidates for a dental ceramic.

Acknowledgments

The authors would like to thank Kasetsart University Research and Development Institute (KURDI) and Faculty of Engineering, Kasetsart University for funding a post-doctoral scholarship as well as Faculty of Dentistry, Mahidol University for supports with the analytical instruments and workspace.

Disclosure of potential conflicts of interest

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Research Council of Thailand (TH) [1180364].

ORCID

Duangrudee Chaysuwan [http://orcid.org/0000-0001-6980-4646

References

[1] Bai K, No KS, Chun JSS, et al. Mechanical properties of mica glass-ceramics. J Am Ceram Soc. 1995;78 (5):1217–1222.

[2] Chaysuwan D, Sirinukunwattana K, Kanchanatawewat K, et al. Machinable glass-ceramics forming as a restorative dental material. Dent Mater J. 2011;30(3):358–367.

[3] Höland W, Beall GH. Applications of Glass-Ceramics. In: Höland W, Beall GH, editors. Glass-ceramic technology. 2nd ed. Hoboken, New Jersey: John Wiley & Sons, Inc.; 2012. p. 252–353.

[4] Höland W, Beall GH. Principles of designing glass-ceramic formation. In: Höland W, Beall GH, editors. Glass-ceramic technology. 2nd ed. Hoboken, New Jersey: John Wiley & Sons, Inc.; 2012. p. 38–43.

[5] Montazerian M, Alizadeh P, Eftekhari Yekta B. Processing and properties of a mica–apatite glass–ceramic reinforced with Y-PSZ particles. J Eur Ceram Soc. 2008 [2008 10 01];28(14):2693–2699.

[6] Ban S. Reliability and properties of core materials for all-ceramic dental restorations. Jpn Dent Sci Rev. 2008 [2008 07 01];44(1):3–21.

[7] Gali S, Ravikumar K, Murthy B.V.S., Basu B. Zirconia toughened mica glass ceramics for dental restorations. Dent Mater. 2018 [2018 03 01];34(3):e36–e45.

[8] Soubelet CG, Albano MP. Mechanical properties and aging behaviour of Y-TZP with 64S bioglass additions for dental restorations. Adv Appl Ceram. 2019 [2019 08 18];118(6):329–339.

[9] Piconi C, Maccagno G. Zirconia as a ceramic biomaterial. Biomaterials. 1999 Jan;20(1):1–25.

[10] Ban S, Suzuki T, Yoshihara K, et al. Effect of coloring on mechanical properties of dental zirconia. J Med Biol Eng. 2014;34(1):24–19. DOI: 10.5405/jmbe.1425.

[11] Thiel N, Stephan M, inventors; Vita Zahnfabrik H Rauter KG, assignee. Coloring liquid for the homogeneous coloring of ceramic materials. United States patent US2007062410A1. 2007.

[12] Srichumpong T, Phokhinchatchanpan P, Thongpun N, et al. Fracture toughness of experimental mica-based glass-ceramics and four commercial glass-ceramics restorative dental materials. Dent Mater J. 2019 Jun;1;38(3):378–387.

[13] Yuan K, Wang F, Gao J, et al. Effect of zircon-based tricolor pigments on the color, microstructure, flexural strength and translucency of a novel dental lithium disilicate glass-ceramic. J Biomed Mater Res B Appl Biomater. 2014 Jan;102(1):98–107.

[14] Llusar M, Calbo J, Badenes JA, et al. Synthesis of iron zircon coral by coprecipitation routes. J Mater Sci. 2001 [2001 01 01];36(1):153–163.

[15] Ozell E, Turan S. Production of coloured zircon pigments from zircon. J Eur Ceram Soc. 2007 [2007 01 01];27(2):1751–1757.

[16] Sun Y, Wang ZY, Tan J, et al. Coloration of mica glass ceramic for use in dental CAD/CAM system. Mater Lett. 2003 Mar;38(2):137–139.

[17] Gawronski A, Patzig C, Höche T, et al. Effect of Y₂O₃ and CeO₂ on the crystallisation behaviour and mechanical properties of glass–ceramics in the system MgO/Al₂O₃/SiO₂/ZrO₂. J Mater Sci. 2015 [2015 02 01];50(4):1986–1995.

[18] Srichumpong T, Angkulipit S, Prasertwong S, et al. Effect of the crystallisation time and metal oxide pigments on translucency and the mechanical and physical properties of mica glass-ceramics. J Non-Cryst Solids. 2020 [2020 01 15];528:117930.

[19] Marotta A, Buri A, Branda F. Nucleation in glass and differential thermal analysis. J Mater Sci. 1981 [1981 02 01];16(2):341–344.

[20] Schindelin J, Arganda-Carreras I, Frise E, et al. Fiji: an open-source platform for biological-image analysis
Conshohocken, fluorescence advanced tistry: editors.

Relative of 8):371–372. El-Meliegy

flame-translucency cations. Translucency

and materials.

and dental ceramics. J Esthet Restor Dent. 2014;26(4):224–231.

and microstructure of a selection of all-ceramic materials. Part II. Zirconia-based dental ceramics. Dent Mater. 2004

and denticity: historical roots and current perspectives. J Prosthodent. 2014;6(5):415–422.

Kurtulmus-Yilmaz S, Ulusoy M. Comparison of the translucency of shaded zirconia all-ceramic systems. J Adv Prosthodont. 2014;6(5):415–422.

Kelly JR, Nishimura I, Campbell SD. Ceramics in dentistry: historical roots and current perspectives. J Prosthodent. 1996;75(1):18–32.

Akin I, Goller G. Effect of CeO2 addition on crystallization behavior, bioactivity and biocompatibility of potassium mica and fluorapatite based glass ceramics. J Ceram Soc Jpn. 2009;117(1367):787–792.

Gawronski A, Patzig C, Höche T, et al. High-strength glass-ceramics in the system MgO/Al2O3/SiO2/ZrO2-Y2O3 – microstructure and properties [10.1039/C3CE40335A]. Cryst Eng Comm. 2013;15(31):6165–6176.

Angkulpipat S, Srichumpong T, Prasertwong S, et al. Relating type of mold materials to crystal morphology and properties of glass-ceramics with ysz additions as a dental material. Chiang Mai J Sci. 2020 [11/2020];47(6):1283–1296.

Traini T, Sinjari B, Pascetta R, et al. The zirconia-reinforced lithium silicate ceramic: lights and shadows of a new material. Dent Mater J. 2016 Oct;1;35(5):748–755.

Gawronski A, Rüssel C. High strength glass–ceramics in the system MgO/Y2O3/Al2O3/SiO2/ZrO2 without quartz as crystalline phase. J Mater Sci. 2013 [2013 05 01];48(9):3461–3468.

Casolco SR, Xu J, Garay JE. Transparent/translucent polycrystalline nanostructured yttria stabilized zirconia with varying colors. Scripta Mater. 2008 [2008 03 01];58(6):516–519.

Li J-F WR. Phase transformation in Y2O3-partially stabilized ZrO2 polycrystals of various grain sizes during low-temperature aging in water. J Am Ceram Soc. 1998;81(10):2687–2691.

Yang D, Raj R, Conrad H. Enhanced sintering rate of zirconia (3Y-TZP) through the effect of a weak dc electric field on grain growth. J Am Ceram Soc. 2010;93(10):2935–2937.

Prasertwong S, Angkulpipat S, Srichumpong T, et al. Tribology, mechanical properties and coloration of a mica glass-ceramic. J Met Mater Miner. 2020 06 30;30(2):83–90.

Stawarczyk B, Emslander A, Roos M, et al. Zirconia ceramics, their contrast ratio and grain size depending on sintering parameters. Dent Mater. 2014;33(5):591–598.

Vichi A, Carrabba M, Paravina R, et al. Translucency of ceramic materials for CEREC CAD/CAM system. J Esthet Restor Dent. 2014;26(4):224–231.

Dietschi D, Ardu S, Krejci I. A new shaping concept based on natural tooth color applied to direct composite restorations. Quintessence Int. 2006 Feb;37(2):91–102.

Vichi A, Sedda M, Fabian Fonzar R, et al. Comparison of contrast ratio, translucency parameter, and flexural strength of traditional and “augmented translucency” zirconia for CEREC CAD/CAM system. J Esthet Restor Dent. 2016 Mar;28(Suppl 1):532–9.

Yu B, Ahn JS, Lee YK. Measurement of translucency of tooth enamel and dentin. Acta Odontol Scand. 2009;67(1):57–64.

Guazzato M, Albayrak M, Ringer SP, et al. Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part II. Zirconia-based dental ceramics. Dent Mater. 2004 Jun;20(5):449–456.

Baik DS, No KS, Chun JS, et al. Effect of the aspect ratio of mica crystals and crystallinity on the micro-hardness and machinability of mica glass-ceramics. J Mater Process Tech. 1997 [1997 05 01];67(1):50–54.

Anusavice KJ. Degradability of dental ceramics. Adv Dent Res. 1992 [1992 09 01];6(1):82–89.