1. Introduction

Dental prostheses are used to restore the shape, mechanical functions, and aesthetic function of teeth lost due to cavities, periodontal disease, or accident. In the field of dental care, significant emphasis is placed on the appearance of prostheses, including esthetic blending with adjacent teeth and reproduction of natural tooth coloration. Esthetic dental treatment satisfies demand for whitened teeth, improving quality of life. Porcelain-fused-to-metal crowns have long been used for repairing teeth. Because these crowns have metal frames, however, the gingiva near the cervical part may appear dark, and blackening may occur where the metal comes into contact with the gingiva. Since the prosthesis is placed in the harsh environment of the oral cavity over long periods, metal allergy due to eluate from the metal frame has proved to be a problem, prompting the development of new methods for tooth repair. Zirconia ceramics are used in dental prostheses for tooth restoration because of their excellent strength and high biocompatibility. They are widely used clinically for cosmetic dentistry. This study evaluates the suitability of yttria-based zirconia and ceria-based nano-zirconia for use in dentistry. The mechanical properties of zirconia powders with different compositions are evaluated in terms of sintering density, crystalline phases, structure, translucency, bending strength, fracture toughness, and impact toughness. In addition, a fracture strength test was carried out on sintered bodies that imitate a single crown coping assuming a molar tooth. Yttria-based zirconia was found to have a natural tooth tone and excellent light transmission. Ceria-based nano-zirconia was found to have more than double the fracture toughness (single-edge pre-cracked beam method) and bending strength compared to yttria-based zirconia and excellent strength for dental prostheses. Such as computer-aided design/computer-aided manufacturing (CAD/CAM). Such prostheses reduce the risk of metal allergy [2]. In general, ceramics have become widely used as alternative materials in sites where metallic materials have traditionally been used, such as implant materials and artificial joints, due to their excellent chemical stability and mechanical properties. However, one disadvantage of ceramics is that their tensile strength and impact strength are inferior to those of metal materials. Because ceramics are hard and brittle, their long-term reliability is poor, and there are constraints on their use for parts that require impact resistance. Fracture toughness is an index of impact strength (i.e. brittleness). Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) has high fracture toughness [3]. When stress is applied to Y-TZP, the crystal structure is transformed from tetragonal to monoclinic, with a volume expansion of about 4%; this is called stress-induced phase transformation. Compressive stress that acts on the tips of generated cracks is also produced, preventing crack propagation [4,5]. Although Y-TZP exhibits excellent chemical stability, low-temperature deterioration occurs in hydrothermal environments, in which the phase is transformed from tetragonal to monoclinic, degrading the mechanical properties. This phase transformation is considered to be one cause of strength deterioration. To function stably in the harsh environment of the oral cavity over the long term, excellent durability is required.
A ceria-stabilized tetragonal zirconia-based nanocomposite ceramic (ceria-based nano-zirconia) was developed by Nawa et al. [6,7]. This material incorporates alumina nanoparticles into the crystal grains of tetragonal zirconia stabilized with ceria (Ce-TZP). Similarly, Ce-TZP nanoparticles are incorporated into the alumina crystal grains. As a result, nano-zirconia has high fracture toughness and excellent resistance to low-temperature deterioration [8]. These characteristics allow a ceria-based nano-zirconia frame with a thickness of only 0.3 mm (similar to that for metal) to be used for prostheses, reducing the required cutting of abutment teeth [9]. As described above, although ceria-based nano-zirconia has excellent mechanical properties compared with those of Y-TZP, it has minimal translucency, which is important for tooth color reproduction. Porcelain materials must thus be used for facing teeth in combination with dental techniques to reproduce the color tones of natural teeth or adjacent teeth. By contrast, this opacity can negate the influence of the material and color of abutment teeth, with the resulting advantage that the procedure can be conducted using the same buildup techniques as in fabricating crowns made of porcelain-fused-to-metal. Ceria-based nano-zirconia, which has excellent mechanical properties and biocompatibility, may therefore offer high clinical value as a replacement for metal.

This study compares yttria-based zirconia and ceria-based nano-zirconia, which are widely used in dentistry. The mechanical properties of zirconia powders with different compositions are evaluated in terms of translucency, sintering density, crystalline phases, structure, bending strength, fracture toughness, and impact toughness. In addition, a fracture strength test is carried out on sintered bodies that imitate single crown copings assuming a molar tooth.

2. Material and methods

2.1. Preparation of samples

One type of zirconia powder containing ceria as a stabilizer (sample MA) and three types of zirconia powder containing yttria as a stabilizer (samples TZ, ZP, and ZS) were prepared (Table 1). Each zirconia powder was pre-formed in a mold and molded at a pressure of 196 MPa with cold isostatic pressing.

The molded bodies were cut using a CAD/CAM system to the required dimensions for each test. Each specimen was sintered in an electric furnace at 1723 K in the ambient atmosphere for 2 hours.

2.2. Density, transmittance, crystal phases, and surface texture observations

Density was measured using the Archimedes method for mirror-polished zirconia sintered bodies (20.0 × 20.0 × 1.0 mm). Total light transmittance was measured using a turbidimeter (NDH 2000; Nippon Denshoku Industries Co., Ltd., Tokyo, Japan) for the zirconia sintered bodies used for density measurements. The crystal phases of the zirconia sintered bodies (20.0 × 20.0 × 1.0 mm) were identified using X-ray diffraction (XRD) analysis (CuKα, 40 kV, 40 mA, Ultima IV; Rigaku Co., Tokyo, Japan). For observation of the surface texture, mirror-polished zirconia sintered bodies (20.0 × 20.0 × 1.0 mm) were thermally etched at 1273 K for 30 minutes, and the fine structure was observed using scanning electron microscopy (SEM; S-3500N; Hitachi High-Technologies Corp., Tokyo, Japan). The average particle size of the crystal grains was estimated using the planimetric method [10].

2.3. Flexural strength test

To measure bending strength, a biaxial flexure test and a three-point bending test were conducted according to ISO 6872:2015 [11]. In the biaxial flexure test, ten mirror-polished zirconia sintered bodies (diameter: 14.0 mm; thickness: 1.3 mm) were prepared and tested with a universal testing machine (Autograph AG-X; Shimadzu Corp., Kyoto, Japan). In the test, three hardened heat-treated steel balls with diameters of 4.0 mm were arranged at 120° intervals on a support circle with a diameter of 11.0 mm. The end face of a cylinder with a diameter of 1.4 mm was loaded at a crosshead speed of 1.0 mm/min in the center of the upper surface of test pieces placed concentrically on the steel balls. The biaxial flexure strength was calculated using Equation (1). Poisson’s ratio ν was set to 0.31 for each zirconia sample.

\[
\sigma = \frac{-0.2387P(X - Y)}{b^2}
\]  

Table 1. Materials used in this study.

| Code | Product name                     | Composition | XRF analysis value (wt%) | Primary particle size (nm) |
|------|----------------------------------|-------------|--------------------------|---------------------------|
| MA   | MACZ-100L (Daichik Kigenso Kagaku Kogyo) | 10 mol% CeO₂-ZrO₂, 30 vol% Al₂O₃ | ZrO₂ + HfO₂, CeO₂, Y₂O₃, Al₂O₃ | 76.6, 11.0, 12.4, 50 |
| TZ   | TZ-3YSB-E (Tosoh)                | 3 mol% Y₂O₃-ZrO₂ | 94.3, - , 5.44, 0.26, 90 |
| ZP   | Zpex (Tosoh)                     | 3 mol% Y₂O₃-ZrO₂ | 94.0, - , 5.95, 0.05, 40 |
| ZS   | ZpexSmile (Tosoh)                | 5 mol% Y₂O₃-ZrO₂ | 89.8, - , 10.1, 0.06, 90 |
where

\[ \sigma \] is the maximum tensile stress at the center (MPa)
\[ P \] is the total load causing fracture (N)
\[ b \] is the specimen thickness at the fracture origin (mm)
\[ X = (1 + \nu)\ln \left( \frac{r_2}{r_3} \right)^2 + \left[ (1 - \nu)/2 \right] \left( \frac{r_2}{r_3} \right)^2 \]
\[ Y = (1 + \nu) \left[ 1 + \ln \left( \frac{r_1}{r_3} \right)^2 \right] + (1 - \nu) \left( \frac{r_1}{r_3} \right)^2 \]

where

\[ \nu \] is Poisson’s ratio
\[ r_1 \] is the radius of the support circle (mm)
\[ r_2 \] is the radius of the loaded area (mm)
\[ r_3 \] is the radius of the specimen (mm)

In the three-point bending test, 30 mirror-polished zirconia sintered bodies (width: 4.0 mm; length: 20.0 mm; thickness: 1.2 mm; chamfer: 0.1 mm) were prepared as specimens and tested with a universal testing machine (EZ-Graph; Shimadzu Corp.). In the test, a load was applied at a crosshead speed of 1 mm/min using a jig with a support point distance of 14.0 mm and support rod and load plunger diameters of 1.6 mm. The three-point bending strength was calculated using Equation (2):

\[ \sigma = \frac{3P}{2wb^2} \]  

where

\[ \sigma \] is the three-point bending strength (MPa)
\[ P \] is the breaking load (N)
\[ l \] is the test span (mm)
\[ w \] is the width of the specimen (mm)
\[ b \] is the thickness of the specimen (mm)

2.4. Fracture toughness test

A fracture toughness test was conducted according to ISO 15,732:2003 [12] using the single-edge pre-cracked beam (SEPB) method. Five mirror-polished zirconia sintered bodies (width: 4.0 mm; thickness: 3.0 mm; length: 40.0 mm; chamfer: 0.1 mm) were prepared and tested with a universal testing machine (Model 5582; Instron Inc., MA, USA). A jig with a support point distance of 16.0 mm and a supporting tool with a diameter of 4.0 mm were used in the test. A load was applied at a crosshead speed of 0.5 mm/min. The fracture toughness value \( K_{ic} \) was calculated using Equation (3):

\[ K_{ic} = \left( \frac{P \times S}{B \times W^2} \right) \times \left\{ \frac{3}{2} \left( \frac{a}{W} \right)^{\frac{1}{2}} \times Y\left( \frac{a}{W} \right) \right\} \]  

\[ Y\left( \frac{a}{W} \right) = \frac{1.99 - 0.4 \left( 1 - \frac{a}{W} \right) \times \left\{ 2.15 - 3.93 \frac{a}{W} + 2.7 \left( \frac{a}{W} \right)^2 \right\} \times (1 + 2 \frac{a}{W}) \times (1 - \frac{a}{W})^{\frac{1}{2}}}{(1 + 2 \frac{a}{W}) \times (1 - \frac{a}{W})^{\frac{1}{2}}} \]

where

\[ K_{ic} \] is the fracture toughness (MPa/m)
\[ P \] is the breaking load (N)
\[ S \] is the support span (mm)
\[ B \] is the specimen length (mm)
\[ W \] is the specimen width (mm)
\[ a \] is the pre-crack length (mm)

To determine the influence of the test method, fracture toughness value \( K_{ic} \) was also obtained using Niihara’s equations [13], Equations (4) and (5) below, by the indentation fracture (IF) method based on the crack length at the corner of a Vickers indentation. To initiate a crack, a Vickers indenter was pressed into a mirror-polished zirconia sintered body (10.0 × 10.0 × 3.0 mm) using a hardness tester (HV-113; Mitutoyo Corp., Kanagawa, Japan) with a test force of 196 N and a load time of 15 s.

For Palmqvist cracks,

\[ \left( \frac{K_{ic}}{H \times a^2} \right) \times \left( \frac{H}{E} \right)^{\frac{1}{2}} = 0.018 \times \left( \frac{I}{a} \right)^{\frac{1}{2}} \]  

For median cracks,

\[ \frac{K_{ic}}{H \times a^2} = 0.203 \times \left( \frac{c}{a} \right)^{\frac{1}{2}} \]  

where

\[ K_{ic} \] is the fracture toughness (MPa/m)
\[ a \] is half the diagonal length of the indentation (m)
\[ c \] is half the crack length from the corner of the indentation of the median crack (m)
\[ I \] is half the crack length from the corner of the indentation of the Palmqvist crack (m)
\[ E \] is the Young’s modulus (Pa)
\[ H \] is the Vickers hardness

2.5. Impact resistance test

In the impact test (ball drop test), zirconia sintered bodies processed to a diameter of 15 mm and a thickness of 1 mm were fixed on a steel plate with resin cement (Super Bond; Sun Medical Co., Ltd., Shiga, Japan), and steel balls (7, 14, 24, 33, 65, 112, 175, 261, 372, and 508 g) were dropped (free fall) from a height of 60 cm above the sintered bodies (Figure 1).

In the test, three test specimens were prepared for each steel ball weight, and the impact force was calculated using Equation (6) from the weight of the steel ball that broke the specimen in at least one of the three tests for that weight. The free-fall velocity was constant and the collision time was 1 ms.

\[ F = \frac{m \sqrt{2gh}}{\Delta t} \]  

where

\[ F \] is the impact force (N)
\[ m \] is the weight of the steel ball (kg)
$g$ is the gravity acceleration (m/s$^2$)
$h$ is the falling distance (m)
$\Delta t$ is the collision time (s)

A fracture strength test of zirconia sintered bodies that imitate a single crown coping assuming a molar tooth was carried out using a centralized loading method with a universal testing machine (EZ-Graph; Shimadzu Corp., Figure 2). The thickness of the zirconia coping was 0.5 mm (for sample MA, a thickness of 0.3 mm was also added), and the surface was buffed with 1 $\mu$m diamond paste. The zirconia coping was fixed with resin cement (Super Bond; Sun Medical Co., Ltd., cement space set to 100 $\mu$m). In the test, a steel ball with a radius of 2 mm was loaded at the center of the upper surface of the specimen at a velocity of 1 mm/min. A resin (KZR-CAD HR3 Gammatheta; YAMAKIN Co., Ltd., Kochi, Japan) with an elastic coefficient close to that of a natural tooth was used for the abutment.

### 3. Results

#### 3.1. Density, transmittance, crystal phases, and surface texture observations

The appearance, transmittance, and density of each zirconia sintered body are shown in Table 2. Sample MA (ceria-based nano-zirconia) was pale yellow in color and opaque, preventing the line drawn under the sample from being discernable. By contrast, samples TZ, ZP, and ZS (yttria-based zirconia) were white and translucent, making the lines drawn under the samples clearly discernable. Sample ZS had notably higher translucency than samples TZ and ZP. The samples’ translucency did not deteriorate due to residual pores, since its relative density was 99.8% or above in every case. Sample ZS had the highest transmittance (51%), followed by samples ZP (43%) and TZ (33%). For sample MA, the transmittance was 0% when the thickness of the test piece was 1.0 mm.

The results of XRD analysis of each zirconia sintered body are shown in Figure 3. The XRD pattern for sample MA has a peak corresponding to tetragonal Ce-doped zirconia and a small peak corresponding to alumina. As concerns yttria-based zirconia, the XRD patterns for samples TZ and ZP have peaks corresponding only to tetragonal zirconia, whereas sample ZS has peaks corresponding to a eutectic mixture of tetragonal zirconia and cubic zirconia.

The surface texture of each zirconia sintered body is shown in Figure 4. The average particle size of sample MA obtained using the planimetric method was about 0.6 $\mu$m. Dark particles measuring about 0.5 $\mu$m can be observed in a part of the particle structure. These are alumina particles, as determined using energy-dispersive X-ray spectroscopy (data not shown). The particles measuring about 1.0 $\mu$m are Ce-TZP.

### Table 2. Outer appearance, transmittance, and density of each sintered zirconia specimen.

| Appearance (Thickness: 0.5 mm) | MA | TZ | ZP | ZS |
|-------------------------------|----|----|----|----|
| Transmittance (%) (Thickness: 1.0 mm) | 0  | 33 | 43 | 51 |
| Density (g/cm$^3$) | 5.54 | 6.06 | 6.07 | 6.03 |
| Relative density (%) | 100 | 99.9 | 99.9 | 99.8 |
addition, it was observed that 10 to 20 nm particles were dispersed with respect to one another in larger particles. Sample TZ contained particles measuring about 0.5 μm as well as some alumina particles. Sample ZP contained homogeneous particles of about 0.5 μm. Slightly larger particles (0.9 μm) were observed in sample ZS. Samples ZP and ZS did not contain alumina particles.

3.2. Flexural strength

The flexural strength of each zirconia sintered body is shown in Figure 5. Samples TZ and ZP had similar biaxial flexure strength values (1384 and 1378 MPa, respectively). The values for samples MA and ZS were 1275 and 856 MPa, respectively. The three-point bending strength was the highest for sample TZ at 1278 MPa. Samples MA and ZP had similar values (1082 and 1079 MPa, respectively). The value for sample ZS was 770 MPa. The biaxial flexure strength of each sample was 10% higher than the corresponding three-point bending strength.

3.3. Fracture toughness

The fracture toughness values for the respective zirconia sintered bodies obtained using the SEPB method and the IF method are shown in Figure 6. For the SEPB method, sample MA shows the highest value (12.1 MPa·m$^{1/2}$), followed by samples TZ (4.5 MPa·m$^{1/2}$), ZP (4.3 MPa·m$^{1/2}$), and ZS (2.6 MPa·m$^{1/2}$).

Optical microscopy photographs of indentations caused by press fit failures by the Vickers indenter employed in the IF method are shown in Figure 7. The crack length (measured from the corner of the indentation) in sample MA is shorter than those in samples TZ, ZP, and ZS and close to that of a plastically deforming metallic material. In addition, the vertical section of the indentation has a semi-elliptical shape from the corner of the indentation to the crack tip, indicating that a Palmqvist crack was generated initially. In samples TZ, ZP, and ZS, longer cracks are initiated at the corner of the indentations. The vertical section of the indentations show a median crack with a semi-circular shape extending from the crack tip to the diagonal crack tip. In sample ZS, in particular, lateral cracks that are considered to have occurred during unloading appear in a circular pattern around the indentation, and...
median cracks also appear. In sample MA, the form of the crack generated by the indentation is that of a Palmqvist crack, and, moreover, the crack length is less than 1.5 times the diagonal length of the indentation. The fracture toughness value $K_{IC}$ was calculated using Equation (4). Samples TZ, ZP, and ZS exhibited a form of median crack. In each case, the crack length was more than 2.5 times greater than the diagonal length of the indentation, as calculated using Equation (5). Sample MA showed the highest fracture toughness (21.3 MPa·m$^{1/2}$), followed by samples TZ (5.5 MPa·m$^{1/2}$), ZP (5.4 MPa·m$^{1/2}$), and ZS 3.2 (MPa·m$^{1/2}$).

### 3.4. Impact strength

The results of a single impact test for each zirconia sintered body are shown in Figure 8. Sample MA exhibited the highest impact strength (1742 N), followed by samples TZ (600 N), ZP (223 N), and ZS (113 N).

The results of fracture strength tests of sintered bodies that imitate a single crown coping assuming a molar tooth are shown in Figure 9. Sample MA showed the highest fracture strengths (2428 and 2067 N for coping thicknesses of 0.5 and 0.3 mm, respectively), followed by samples TZ (1425 N), ZP (1083 N), and ZS (441 N).

### 4. Discussion

#### 4.1. Light transmission

The values of the composition analysis shown in Table 1, reveal that sample MA is opaque because it contains 11.0 wt% ceria as a stabilizer and 12.4 wt% alumina. The ceria gave sample MA its pale yellow color. By contrast, samples TZ, ZP, and ZS (yttria-based zirconia) are white and translucent, and the lines drawn under the samples are clearly discernable. Sample TZ was found to contain 5.44 wt% yttria as a stabilizer and 0.26 wt% alumina as a sintering agent.
The addition of alumina improved its mechanical strength and resistance to hydrothermal deterioration [14]. The alumina was segregated at the grain boundary of the zirconia after sintering (Figure 4), and light scattering occurred due to the difference in the refractive index between zirconia and alumina, decreasing the light transmittance. Sample ZP contained 5.95 wt% yttria and only 0.05 wt% alumina. Since alumina was not segregated at the grain boundary of the zirconia, light scattering was suppressed and the light transmittance was high as a result. Sample ZS contained 0.06 wt% alumina (about the same as sample ZP), moreover, and 10.1 wt% yttria (more than samples TZ and ZP). It can be seen from the phase diagram [15] and XRD results (Figure 3) that increases in yttria as a stabilizer were accompanied by the formation of cubic zirconia in addition to tetragonal zirconia. Samples TZ and ZP, which contained small amounts of yttria, were tetragonal zirconia polycrystal (TZP). Sample ZS, which had a high yttria content, was partially stabilized zirconia, a eutectic mixture of tetragonal zirconia and cubic zirconia. The proportion of tetragonal zirconia was estimated to be about 50%. Since tetragonal zirconia is a uniaxial anisotropic body, it lowers light transmittance due to light scattering in the crystal. By contrast, cubic zirconia is an optically isotropic body characterized by low light scattering and excellent translucency. Sample ZS is characterized by high translucency caused by the formation of cubic zirconia due to an increase in the content of yttria. Sample MA did not exhibit translucency at a thickness of 1.0 mm, making it unsuitable for a crown bridge as a monolithic zirconia prosthesis from an aesthetic point of view. It is possible to obtain...
sufficient esthetics, however, by combining porcelain with zirconia to build it up and firing it in crown form.

4.2. Mechanical properties

The bending strength test showed the biaxial flexure strength to be about 10% greater than the corresponding three-point bending strength for all the samples. This is because the biaxial flexure strength test is less influenced by cracks present at the edge of a specimen, and thus provides a highly reliable value. A one-way analysis of variance was performed on the bending strength values obtained using the biaxial flexure test and the three-point bending test. A significant difference was observed between samples MA and ZP ($p < 0.01$), and no significant difference was observed between samples TZ and ZS ($p > 0.05$). For samples MA, TZ, and ZP, moreover, no significant difference was observed in the biaxial flexure test ($p > 0.05$), but a significant difference was observed in the three-point bending test ($p < 0.01$). Thus, the test method and test piece processing affected the results. Sample ZS, which had the lowest bending strength among the zirconia sintered bodies, was about 60% weaker than samples TZ and ZP (as well as than yttria-based zirconia). This lower strength of sample ZS was considered to be due to the increased particle size of the sintered body [16,17], the coexistence of cubic zirconia, a smaller proportion of tetragonal zirconia, and less strengthening via stress-induced phase transformation.

As mentioned above, fracture toughness is used as an index of impact strength (i.e. brittleness). Among ceramic materials, tetragonal zirconia with yttria or ceria as a stabilizer exhibits particularly high fracture toughness. This is due to the stress-induced phase transformation mechanism, a feature found only in zirconia among ceramics. Various methods of measuring fracture toughness have been reported. The index to the ISO 6872:2015 dental ceramic material standard recommends the single-edge V-notch beam (SEVNB) method as a reference. Alternative methods include the SEPB method, the surface crack in flexure method, and the chevron notched beam method. However, it is considered impossible to obtain the crack length from the corner of the Vickers indentation. The ISO 15732:2003 standard test method for room-temperature fracture toughness of fine ceramics specifies that the IF method should be derived from the SEPB method and the crack length from the corner of the Vickers indentation. The SEVNB method recommended for the ISO 6872:2015 dental ceramic material standard is greatly influenced by the method used to form the V notch tip, making it difficult to conduct a test with good reproducibility.

In this study, therefore, fracture toughness was evaluated using the SEPB method adopted by ISO 15732:2003. Evaluation using the IF method was also conducted for further comparison. In both the SEPB method test and the IF method test, sample MA showed significantly higher fracture toughness values than samples TZ, ZP, and ZS (yttria-based zirconia). Samples TZ, ZP, and ZS showed comparable values obtained using the SEPB method and the IF method. For sample MA, the value obtained using the IF method was significantly higher than that obtained using the SEPB method, and large variations were also seen. This was because sample MA had greater toughness that made cracks from the corners of the Vickers indentation unlikely to occur, leading to large variations. Sample MA showed an impact resistance that exceeded those of samples TZ, ZP, and ZS in the impact test (ball drop test) with an instantaneous impact load. Sample MA also showed
higher values than samples TZ, ZP, and ZS in the breaking strength test assuming bruxism in the oral cavity. Sample MA was found to have excellent mechanical properties, combining high instantaneous impact resistance and high breaking strength.

5. Conclusions

The present study evaluated the mechanical properties of yttria-based zirconia and ceria-based composite zirconia as dental materials. The following conclusions were obtained:

(1) In the flexural strength test, sample TZ (yttria-based zirconia) containing 0.26 wt% alumina exhibited the highest values among the respective zirconia samples, with biaxial flexure strength of 1384 MPa and three-point bending strength of 1278 MPa.

(2) Sample MA (ceria-based composite zirconia) had the greatest fracture toughness: 12.1 MPa·m$^{1/2}$ for the SEPB method and 21.3 MPa·m$^{1/2}$ for the IF method.

(3) Sample ZS (yttria-based zirconia) had the least bending strength and fracture toughness; however, its white coloring and high translucency make it optimal for use as a full-crown prosthesis for short spans (e.g. front teeth).

(4) Sample MA (ceria-based composite zirconia) did not exhibit translucency, but it can be applied to long-span bridges due to its excellent fracture toughness and flexural strength.

Disclosure statement

No potential conflict of interest was reported by the authors.

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