

Evaluation of the physical properties of an endodontic Portland cement incorporating alternative radiopacifiers used as root-end filling material

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Abstract

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Aim To investigate the physical and chemical properties of Portland cement (PC) loaded with alternative radiopacifying materials for use as root-end filling materials in a mineral trioxide aggregate (MTA)-like system.

Methodology Portland cement loaded with barium sulphate, gold and silver/tin alloy was mixed with water, and the physical and chemical properties of the hydrated cements were evaluated. MTA and intermediate restorative material (IRM) were used as controls. The radiopacity was compared to the equivalent thickness of aluminium, and the setting time of the cements was assessed using an indentation technique. The compressive strength and the stress–strain relationship were determined at 28 days. The stress–strain relationship was determined by monitoring the strain generated when the cement was subjected to compressive load. In addition, the pH was determined in water and simulated body fluid for a period of 28 days.

Results The radiopacity of the cements using alternative radiopacifiers was comparable to MTA

($P > 0.05$). IRM demonstrated a higher radiopacity than all the materials tested ($P < 0.05$). All the cements with the exception of IRM exhibited an alkaline pH and had an extended setting time when compared to IRM. MTA had a longer setting time than the PC ($P < 0.001$), and its setting time was similar to the gold-loaded cement ($P = 0.159$). The addition of a radiopacifier retarded the setting time ($P < 0.001$) but did not have any effect on the compressive strength as all loaded cements had comparable strength to PC ($P > 0.05$). IRM was the weakest cement tested ($P < 0.001$). The cement loaded with gold radiopacifier had comparable strength to MTA ($P = 1$). The stress–strain relationship was linear for all the cements with IRM generating more strain on loading.

Conclusions Within the parameters set in this study, bismuth oxide in MTA can be replaced by gold or silver/tin alloy. The physical, mechanical and chemical properties of the cement replaced with alternative radiopacifiers were similar and comparable to ProRoot MTA.

Keywords: calcium silicate cements, physical properties, radiopacifiers, root-end filling materials.

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Introduction

Mineral trioxide aggregate (MTA) is used primarily to seal lateral root perforations (Lee *et al.* 1993, Pitt Ford *et al.* 1995) and as a root-end filling material

(Torabinejad *et al.* 1995b, 1997, Chong *et al.* 2003, Saunders 2008). MTA is currently commercially available as ProRoot MTA (Tulsa Dental Products, Tulsa, OK, USA) and MTA-Angelus (Angelus Soluções Odontológicas, Londrina, Brazil).

ProRoot MTA is composed mainly of 53.1% tricalcium silicate, 22.5% dicalcium silicate, 21.6% bismuth oxide and small proportions of tricalcium aluminate and calcium sulphate (Camilleri 2008b). The bismuth oxide was added to commercial Portland cement (PC) to enhance the radiopacity of the material (Torabinejad & White 1995). PC has been reported to have intrinsic radiopacity values ranging from 0.86- to 2.02-mm aluminium (Al) (Islam *et al.* 2006, Kim *et al.* 2008, Saliba *et al.* 2009), values lower than the 3-mm Al recommended by the International Standards for dental root canal sealing materials (ISO 6876 2002). Thus, a radiopacifying material has to be added to PC to allow the cement to be detected radiographically and thus distinguished from surrounding anatomical structures (Beyer-Olsen & Ørstavik 1981). Radiopacity is one of the ideal properties of a root-end filling material (Grossman *et al.* 1988).

The ideal radiopacifying material should only impart the necessary radiopacity to the cement and should be inert, free from any contaminants, nontoxic and be added in minimal amounts. Addition of minimal amounts of any material necessitates the use of elements that have a high relative atomic mass. The bismuth oxide in MTA has a high relative molecular mass, and an addition of 20% to PC increased the radiopacity to between 5.34 and 8.26 mm thickness of Al (Laghios *et al.* 2000, Chng *et al.* 2005, Danesh *et al.* 2006, Islam *et al.* 2006, Kim *et al.* 2008, Camilleri & Gandolfi 2010) which is higher than that recommended by ISO 6876 (2002). The increase in radiopacity is inversely proportional to the water to cement ratio of the material (Coomaraswamy *et al.* 2008). Bismuth oxide in MTA is not inert. It forms part of the hydrated phase forming a structure composed of

calcium silicate–bismuth hydrate, and the rest is leached together with calcium hydroxide formed from the hydration of the calcium silicates (Camilleri 2008b). The precipitation of calcium hydroxide in the hydrated paste is reduced in MTA compared to a PC with no addition of bismuth oxide (Camilleri 2007). In addition, it has been demonstrated that bismuth oxide is deleterious to the physical properties of MTA and other bismuth oxide containing materials (Camilleri 2008a) in a dose related manner (Coomaraswamy *et al.* 2007).

Alternative radiopacifying materials with a high relative molecular mass can be used to replace the bismuth oxide in MTA. Addition of gold powder, silver/tin alloy and barium sulphate results in a radiopacity value of more than 3-mm Al, which is similar to the value reported for MTA Angelus (Tanomaru-Filho *et al.* 2008). Loading with 25% gold powder and 20% silver/tin alloy renders the PC as radiopaque as ProRoot MTA (Camilleri & Gandolfi 2010).

This study aimed at investigating the physical and chemical properties of PC loaded with alternative radiopacifying materials.

Materials and methods

The materials used in this study are presented in Table 1. All materials were based on PC (BS EN 197-1: 2000, type CEM I) with additions of different radiopacifiers. MTA (MTA White, Dentsply; Tulsa Dental Products) and Intermediate Restorative Material (IRM; Dentsply DeTrey, Konstanz, Germany) were used as controls. The prototype cements were mixed with water at a water to cement ratio of 0.30. The MTA and IRM were mixed according to the manufacturer's instructions.

Evaluation of radiopacity

The experimental protocol was based on ISO 6876 Section 7.8 (2002) for dental root canal sealing

Material	Proportion of CEM 1 Portland cement %	Radiopacifier %	Manufacturer
PC	100	–	Aalborg White, Aalborg, Denmark
PC-Ba	75	25% BaSO ₄	Sigma-Aldrich, Gillingham, UK
PC-Au	75	25% Au	Sigma-Aldrich, Gillingham, UK
PC-Ag/Sn	80	20% Ag/Sn	Degussa Dental GmbH, Hanau, Germany

PC, Portland cement.

Table 1 Different cement types tested for physical properties

materials. Three discs measuring 10 mm in diameter and 1 mm high were prepared for each material and allowed to cure in distilled water at 37 °C for 7 days.

The cement discs were then placed directly on a cassette loaded with a cephalostat type film with an intensifying screen (Kodak, Rochester, NY, USA) adjacent to an 10-step wedge made of Al where each step measured 1 mm in height (Agfa Mamoray; Agfa Gevaert, Mortsels, Belgium) and eight layers lead to obtain a small area of nonexposure. The film was irradiated using a standard X-ray machine (GEC Medical Equipment Ltd., Middlesex, UK) at a tube voltage of 50 kV, current 50 mA, exposure time of 0.05 s and target to film distance of 100 cm. Two radiographs were exposed of the specimens. The radiographs were processed in an automatic processing machine (Clarimat 300, Gendex Dental Systems; Medivance Instruments Ltd., London, UK). A photographic densitometer (PTWdensix, Freiburg, Germany) was used to measure the density of the radiographic images of the specimens, of each Al step and the unexposed part of the film.

The logarithm of the relevant thickness of Al for each material could be calculated from its net radiographic density for each film taking into consideration that specimen thickness was 1 mm. Logarithms of step height were then converted to thicknesses of Al (Watts & McCabe 1999).

Determination of pH

Two grams of cement was mixed on a glass slab and compacted into metal moulds producing discs 10 mm in diameter. Six discs were made for each material. The cements were allowed to cure at 37 °C and 100% humidity for 24 h after which they were removed from the moulds and placed in sealed plastic containers filled with 5 mL of either distilled water or simulated body fluid (SBF). The SBF was prepared as suggested by Kokubo & Takadama (2006) with a final pH of 7.4. pH determinations of the storage solutions using a pH meter (Hanna HI 9811; Hanna Instruments, Woonsocket, RI, USA) were conducted 1, 7, 14, 21 and 28 days from mixing.

Determination of setting time

The setting time was determined in accordance to ISO 9917-1 (2007). A 400-g indenter with a needle attachment having a flat end of diameter 1 mm of was used to determine the setting time. The cements

were mixed at water to cement ratio of 0.30. MTA and IRM were mixed according to the manufacturer's instructions. The mixture was placed in a mould having internal dimensions 8 mm by 10 and 5 mm thick and the surface levelled. After 60 s from the start of mixing, the mould was placed on a metal block measuring 8 mm by 75 and 100 mm, and the whole assembly was placed in a cabinet at 37 °C and 100% humidity. The indenter was then lowered and the indentation made on the cement surface noted. This procedure was repeated at intervals. The setting time was calculated by measuring the time elapsed between the start of mixing and the time when no indentation was visible on the cement surface. The experiment was repeated thrice, and the mean value of setting time was calculated.

Determination of compressive strength

The compressive strength testing was performed as suggested by ISO 9917-1 (2007). The materials were mixed and were compacted in the moulds using amalgam pluggers. The specimen and mould assembly were stored in an incubator at 37 °C and 100% humidity for 1 day after which the cylinders were removed from the moulds and cured in water at 37 °C for 28 days. Fourteen cylinders were prepared for each material tested. The cylinders were compressed using a compression machine (Controls srl, Milan, Italy) with a loading rate of 50 Nmin⁻¹ until they failed. The maximum load required to fracture the samples was noted. Compressive strength was calculated using the formula:

$$\text{Compressive strength} = \frac{\text{Applied load (N)}}{\text{Area (mm}^2\text{)}}$$

Determination of stress–strain relationship

The stress–strain relationship of the materials under study was determined by measuring the strain of the materials whilst under compressive load. Cylinders 6 mm in diameter and 12 mm in length were prepared from each material under study in a similar way as described in the previous section. The cylinders were cured in water at 37 °C for 28 days. A strain gauge type FLA-2-11-3L with gauge length 2 mm (Tokyo Sokki Kenkyujo Co. Ltd., Tokyo, Japan) was attached with adhesive to the side of the cylinder which in turn was placed between the platens of a compression machine (Controls srl). The cylinder was axially loaded in compression at a loading rate of 17 Ns⁻¹ until the

cylinder failed. The strain generated during the application of the compressive force was monitored by the strain gauge. Readings were recorded every 0.25 s. The strain and stress were for the same time interval was thus monitored and the stress–strain relationship of the different materials was evaluated.

Statistical analysis

The data were evaluated using SPSS software (SPSS Inc., Chicago IL, USA). Parametric tests were performed as the data were normally distributed. Normal distribution of data was verified using the Kolmogorov–Smirnov test with $P = 0.05$. Analysis of variance (ANOVA) with $P = 0.05$ and Tukey post-hoc test was used to perform multiple comparison tests.

Results

Evaluation of radiopacity

The results for mean thickness of Al compared to the relevant radiopacifier replacement of the cement and the controls are shown in Fig. 1. All the materials tested with exception of the PC had radiopacity values >3-mm Al which is the limit suggested by ISO 6876 Section 7.8 (2002). The 25% replacement of cement with gold powder and 20% replacement of cement with silver/tin alloy powder displayed radiopacity values similar to ProRoot MTA ($P > 0.05$). IRM demonstrated a higher radiopacity than all the materials tested ($P < 0.05$).

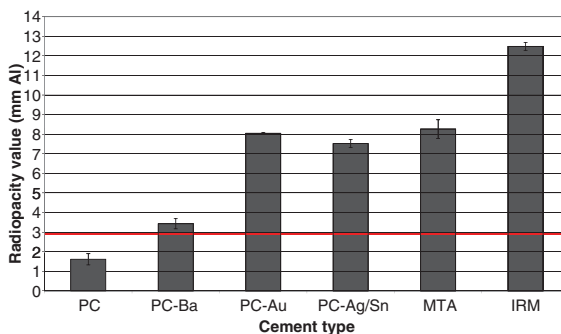


Figure 1 Radiopacity expressed in thickness of aluminium (Al) in mm of mineral trioxide aggregate, intermediate restorative material, Portland cement (PC) and PC replaced with different radiopacifiers. The minimum requirement for radiopacity of an endodontic sealer to meet the ISO 6876 (2002) criteria is equivalent to 3-mm Al.

Determination of pH

The results for the pH changes of water and SBF in contact with the different cements are shown in Fig. 2(a,b), respectively. Both solutions had a neutral pH prior to cement immersion. IRM caused a slight reduction in the pH of water but this change was not statistically significant ($P > 0.05$); it did not affect the pH of the SBF ($P > 0.05$). The PC, the radiopacifier-loaded cements and MTA caused a steep rise in pH in both the solutions tested for the first 7 days which was mostly maintained for 21 days ($P < 0.05$). The pH reduced to 9 after 28 days. In SBF, the MTA and the silver/tin-loaded cement, the pH did not rise significantly after 1 day but it peaked after 7 days.

Determination of setting time

The setting time of the different cements is shown in Fig. 3. All the cements tested with the exception of IRM had extended setting times. IRM set in about 3 min. Addition of radiopacifier to the cement retarded the setting time ($P < 0.001$). MTA had a longer setting time than the PC ($P < 0.001$), and its setting time was similar to the gold-loaded cement ($P = 0.159$).

Determination of compressive strength

The compressive strength of the cements is shown in Fig. 4. Addition of the different radiopacifiers did not have any effect on the compressive strength as all loaded cements had comparable strength to the parent PC ($P > 0.05$). IRM was the weakest cement tested, and it exhibited lower strengths than PC and its derivatives ($P < 0.001$). The cement loaded with gold radiopacifier had comparable strength to MTA ($P = 1$).

Determination of stress–strain relationship

The stress and strain generated with time when the cements were loaded axially in compression is shown in Figs 5 and 6. All the cements exhibited a linear increase in stress with time when subjected axially to a compressive force until the ultimate compressive stress was reached and the specimen failed. On axial loading, all the specimens generally exhibited negative strain. The relationship was linear. The strain generated when testing PC, and its derivatives was within the same range that is from 0 to $4000 \mu\text{m m}^{-1}$. The strain levels of IRM were higher than those sustained

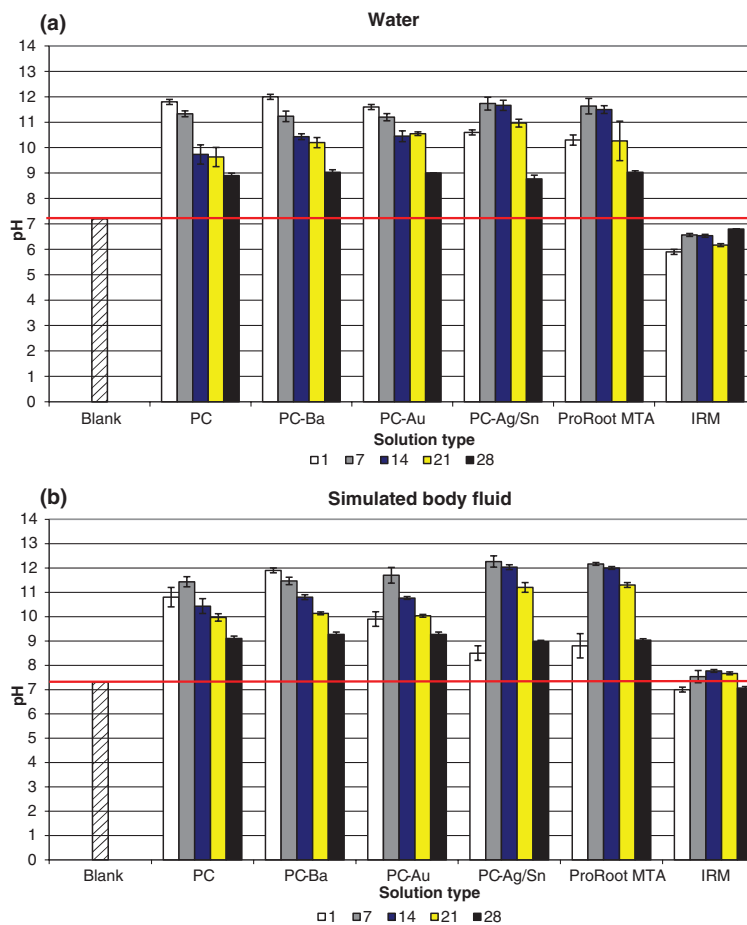


Figure 2 Evaluation of the pH of (a) water and (b) simulated body fluid after immersion of mineral trioxide aggregate, intermediate restorative material, Portland cement (PC) and PC replaced with different radiopacifiers for a period of 28 days.

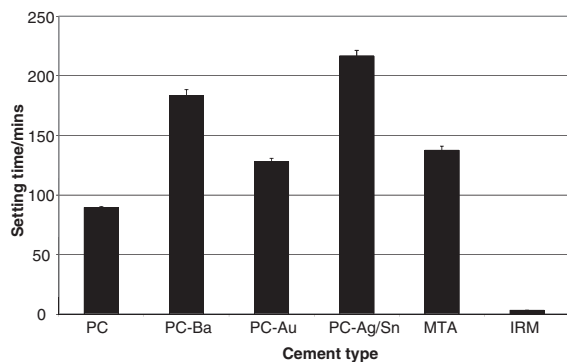


Figure 3 Final setting time in minutes of mineral trioxide aggregate (MTA), intermediate restorative material (IRM), Portland cement (PC) and PC replaced with different radiopacifiers showing the extended setting time exhibited by the MTA, PC and radiopacifier-replaced cements when compared to IRM.

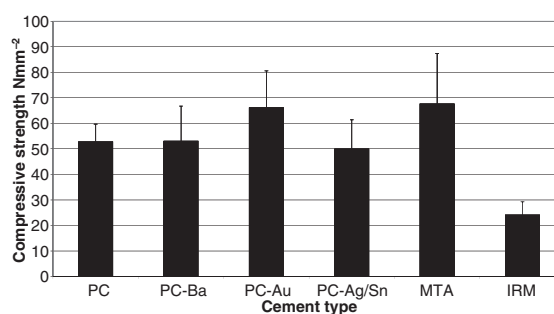


Figure 4 Compressive strength of mineral trioxide aggregate (MTA), intermediate restorative material, Portland cement (PC) and PC replaced with different radiopacifiers after 28 days curing in water at 37 °C showing the comparable strength of MTA to PC-Au.

by the PC, the radiopacifier-loaded cements and MTA. The stress-strain relationship of all the cements tested is shown in Fig. 7. The stress-strain relationship was

mostly linear for all the materials tested. The stress applied resulted in a reduction in length of the specimen leading to negative strain. When the ultimate stress was reached, the specimen failed exhibiting a

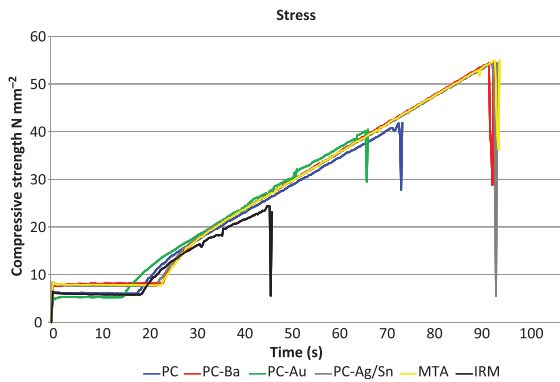


Figure 5 Compressive stress generated with time of mineral trioxide aggregate, intermediate restorative material, Portland cement (PC) and PC replaced with different radiopacifiers demonstrating the brittle nature of the materials tested.

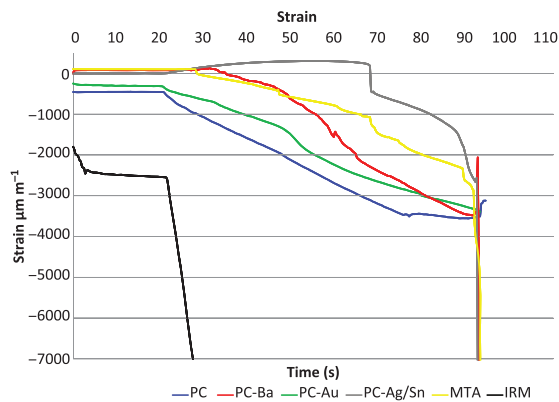


Figure 6 Strain sustained with time of mineral trioxide aggregate, intermediate restorative material, Portland cement (PC) and PC replaced with different radiopacifiers when specimens were loaded in compression. On loading the cements exhibit negative strain until the ultimate stress results in specimen failure.

rapid reduction in stress for the same strain value. The MTA, silver/tin-replaced and barium sulphate-replaced cements exhibited positive strain during the initial stages of loading. Addition of the radiopacifiers did not modify the stress-strain relationship of the cements tested.

Discussion

Material radiopacity

The radiopacifiers used in this study were all metals with high mean relative masses allowing the material to be easily detected on a radiograph whilst enabling

minimum addition of radiopacifier. The barium sulphate exhibited the lowest radiopacity, which was however still greater than the radiopacity value suggested by ISO 6876 Section 7.8 (2002). Barium sulphate is used routinely in gastroenterology as a contrast medium. Silver/tin alloy and gold had similar radiopacities to ProRoot MTA. The silver/tin alloy is one of the constituents of dental amalgam and is thus readily available in dentistry and is considered to be safe for clinical use. Corrosion of silver with time can cause tattooing of the soft tissues overlying the root-end filling. Gold has been used alloyed to other metals and used for cast restorations. The main disadvantage of the use of gold is its colour and high cost. However, considering that the cost of MTA after several years on the market is still high, the addition of gold powder to PC may not be considered as prohibitive. The percentage replacements selected were the minimum amounts of radiopacifiers required to achieve a radiopacity comparable to MTA. The radiopacity of ProRoot in the present study was similar to previous reports (Laghios *et al.* 2000, Chng *et al.* 2005, Danesh *et al.* 2006, Islam *et al.* 2006, Kim *et al.* 2008, Camilleri & Gandolfi 2010). IRM had a radiographic density equivalent to 12.5 mm Al. This value was higher than the values reported for IRM in previous studies (Torabinejad *et al.* 1995a, Shah *et al.* 1996, 1997, Laghios *et al.* 2000, Tanomaru-Filho *et al.* 2008). The IRM exhibited the highest radiopacity of all the materials tested which was higher than that of ProRoot MTA in accordance with previous reports (Laghios *et al.* 2000, Tanomaru-Filho *et al.* 2008) but in contrast to another study where MTA was reported to be more radiopaque than IRM (Torabinejad *et al.* 1995a).

pH

Mineral trioxide aggregate, PC and the cements loaded with the different radiopacifiers exhibited an alkaline pH. This is in accordance to other studies (Torabinejad *et al.* 1995a, Duarte *et al.* 2003, Fridland & Rosado 2003, 2005, Santos *et al.* 2005, Bortoluzzi *et al.* 2009) reporting pHs of 10–12. The alkaline pH is caused by the release of calcium hydroxide from the hydrating cement (Camilleri 2007, 2008b). Changes in the surrounding solution may alter the hydration of the cement with differences in the reaction by-products (Lee *et al.* 2004). In the present study, the effect SBF on the pH of the cements and storage solutions was investigated. The SBF had a pH of 7.4. Although SBF has some buffering capacity, the pH of the storage solution rose immediately to very alkaline with all the

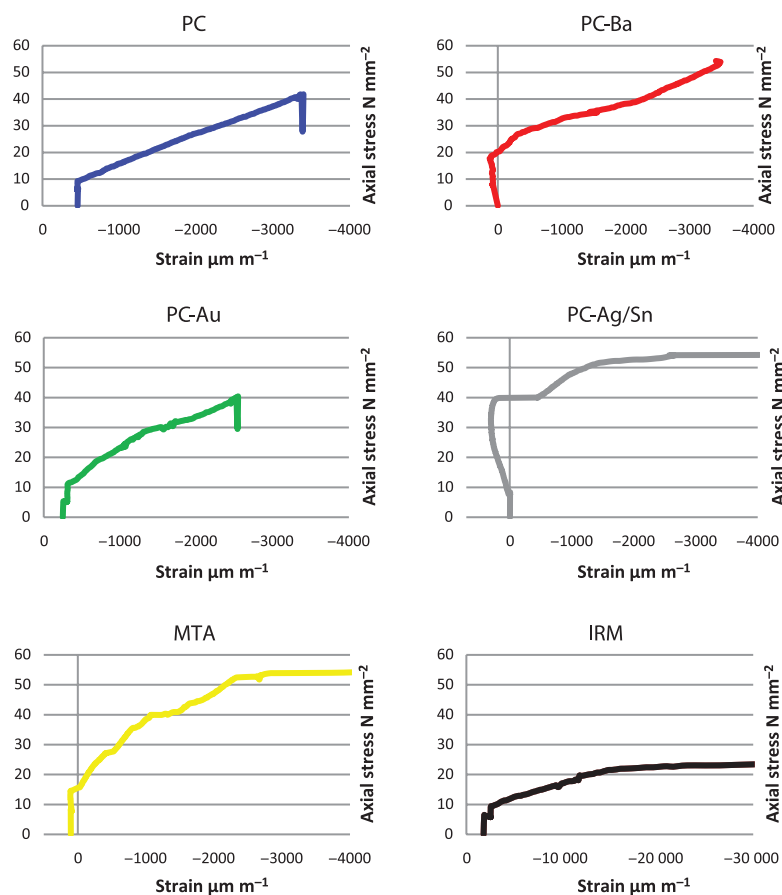


Figure 7 Stress/strain relationship of mineral trioxide aggregate, intermediate restorative material, Portland cement (PC) and PC replaced with different radiopacifiers.

cements based on PC. The MTA and PC replaced with silver/tin alloy exhibited a rise in pH after 7 days exposure to the SBF. This phenomenon could infer differences in the liberation of calcium hydroxide from these cements when compared to the PC and other radiopacifier-replaced cements tested in this study. The reduced calcium ion release in MTA when compared to PC has been reported (Camilleri 2007). Exposure of PC to SBF has been found to promote the precipitation of a bone-like hydroxyapatite on the cement surface thus indicating the ability of the material to integrate with living tissue (Zhao *et al.* 2005). In addition, in the presence of SBF, PC hydroxyapatite formation was induced and the cement dissolved (Zhao *et al.* 2005, Coleman *et al.* 2007). IRM had a slightly acidic pH very likely caused by the acetic acid present in the liquid.

Physical properties

The physical properties of hydraulic cements are dependent on the water/cement ratio (Neville 1981). Replacing the cement with noncementitious materials

increases the effective water/cement ratio which in turn affects both the resultant material strength and the workability. Factors affecting the water/cement ratio included the specific surface area of the powders, the water absorption and the higher relative molecular mass of the radiopacifying materials replacing the cement (Camilleri & Gandolfi 2010). The higher the relative molecular mass, the less radiopacifier added to the mixture to make up for the percentage replacement. Thus, the water/cement ratio was effectively higher. More barium sulphate was added than silver/tin alloy for each percentage replacement. In addition, the barium sulphate and gold powder had a very high specific surface area (Camilleri & Gandolfi 2010); thus, to achieve the same workability, the mixture required more water. Taking all these factors into consideration, it was decided to keep the water/cement ratio constant for all the mixes.

Setting time

The setting time was determined using a 400-g indenter and mould dimensions as suggested by ISO

9917 (2007). This method only determines the final setting time of the cement. The setting time of Portland industrial cements is usually measured using the Vicat apparatus (EN 196-3 2005). This technique is also an indentation technique similar to the method suggested by ISO 9917 (2007). The Vicat measures both initial and final setting times of the cement as opposed to the indenter specified in the international standard (ISO 9917-1 2007). In addition, the EN 196-3 (2005) also includes a standard consistence test. The standard consistence test determines the optimal amount of water required by the mix. An excess of water added will result in deterioration in the physical properties of the material particularly strength whilst a too low water to cement ratio will lead to insufficient water required for complete hydration (Griffith 1920). The main disadvantage of the Vicat test is the size of the mould as to perform the test at least 400 g of cement need to be mixed to fill the mould; this amount is prohibitive for dental materials. Other researchers (Chng *et al.* 2005, Islam *et al.* 2006, Bortoluzzi *et al.* 2009) used ASTM C266-08 (2008) and ANSI/ADA Specification No. 57 (2008). The ASTM C266-08 method is similar the method described in the European standards using the the Vicat apparatus (EN 196-3 2005) which determines both initial and final setting times using the Gilmore needles. The main disadvantage however is the need to use 650 g of cement to fill a mould of dimensions 100 by 5 mm. It is not clear whether researchers using this method have adapted the mould dimensions to take up less material as suggested by Ber *et al.* (2007) who used moulds 10 by 2 mm with the Vicat apparatus instead of the standard truncated cone measuring 70–80 mm wide and 40 mm deep (ISO 9917 2007). The ANSI/ADA Specification No. 57 (2008) describes a similar method to the ISO 6876 (2002). These standard test methods determine the setting time of endodontic filling materials thus utilize an indenter which weighs 100 g as opposed to the 400 g used in ISO 9917 (2007) and 300 g of the Vicat (EN 196-3 2005). In addition, the moulds are 10 by 2 mm smaller than the moulds used in all the other standard test methods.

Although the testing of setting time of dental cements is not standardized, the results for MTA obtained in this study were similar to previous reports (Torabinejad *et al.* 1995a, Chng *et al.* 2005, Islam *et al.* 2006, Ber *et al.* 2007, Bortoluzzi *et al.* 2009). MTA had a longer setting time when compared to PC as previously reported (Islam *et al.* 2006, Ber *et al.* 2007). The addition of any fillers retards the setting

time as the filler prevents cement particle packing, thus formation of a cement matrix takes longer and this extends the final setting time of the material (Neville 1981). MTA is made up of a mixture of PC and bismuth oxide added for radiopacity (Torabinejad & White 1995). The addition of the radiopacifier retarded the setting time. The setting time of IRM was in the range previously reported for this material (Owadally & Pitt Ford 1994).

Compressive strength

The addition of the different radiopacifiers did not affect the compressive strength of the cements. The cements had comparable strength values to the unloaded PC. This is in contrast to previous reports reporting the deterioration in strength of PC with increasing percentage replacements of bismuth oxide (Coomaraswamy *et al.* 2007, Camilleri 2008a) but in accordance to another study reporting no deterioration in physical properties on addition of bismuth oxide (Saliba *et al.* 2009). The variation in the results obtained can be because of the various factors affecting the mechanical testing of PCs (Camilleri *et al.* 2006). These factors include the water/cement ratio, the shape and size of the specimen, end preparation of the specimen, the loading rate (Neville 1981) and packing pressures (Nekoofar *et al.* 2007). The water to cement ratio is one of the most reported parameters affecting the strength of PCs (Griffith 1920). Dilution of MTA has been reported to deteriorate the radiopacity of the material as well (Coomaraswamy *et al.* 2008). Radiopacity is a very important property for root-end filling materials (Grossman *et al.* 1988). The sizes of the moulds also varied in the different reports. The 4 by 6 mm moulds suggested in the ISO standard for testing dental cements (ISO 9917 2007) and used in the present study are also used in previous reports (Torabinejad *et al.* 1995a, Nekoofar *et al.* 2007). Other researchers have used different sized moulds (Islam *et al.* 2006, Ber *et al.* 2007). There is very little experimental evidence on the physical properties of MTA. Only four publications (Torabinejad *et al.* 1995a, Islam *et al.* 2006, Ber *et al.* 2007, Nekoofar *et al.* 2007) report the compressive strength of the MTA. The data obtained in the various studies exhibited a number of variables the most important being the curing time which varied from 24 h to 28 days. The compressive strength of IRM in the present study was lower than that reported in previous research (Owadally & Pitt Ford 1994, Torabinejad *et al.* 1995a).

Stress–strain relationship

The deformation sustained when the specimens were subjected to compressive stress was elastic in nature, and the stress and strain were proportional. The stress–strain relationship of the cements was mostly linear when the stress was applied in compression. The addition of the radiopacifier did not affect the stress–strain relationship. The modulus of elasticity could not be determined as the movements sustained by the gauges whilst the specimen was being tested in compression caused movement in the lateral direction. This was exhibited by the regions of positive strain that were recorded. The modulus of elasticity gives an indication of the type of atomic bonding present (Illston & Damone 2001). PCs have a mixture of covalent and ionic bonds. Both types of atomic bonding are strong thus failure results from any defects present in the atomic structure of the material. Under stress, elastic deformation occurs and the defects present can be critical leading to failure. This type of bonding results in a brittle material. The addition of a radiopacifier did not seem to affect the stress–strain relationship of the material.

Conclusions

Within the parameters set in this study, it has been concluded that the bismuth oxide in MTA can be replaced by gold and silver/tin alloy. The physical, mechanical and chemical properties of the cement replaced with alternative radiopacifiers were similar and comparable to ProRoot MTA. Further investigation regarding the biocompatibility and the interaction of these heavy metals to the Portland matrix is warranted.

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