SYSTEMATIC ANALYSIS OF MINERAL TRIOXIDE AGGREGATE USING A MODEL CEMENT SYSTEM

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ABSTRACT

Mineral trioxide aggregate (MTA) is a Portland cement-based material in use in dentistry for over 20 years. Although originally developed as a root canal reparative material, multiple applications have since been found for the cement. Commercial MTA is expensive, and for research, its composition cannot be changed/modified. This investigation endeavoured to create and validate an affordable MTA model cement system for future research into the material, and use the model created to analyse the cement with view to further understanding it and improving its properties.

An MTA-like model system was established and setting times, compressive strength, relative porosity, apparent and specific densities and radiopacity were measures used to assess cement samples made. Sample storage time, composition, alternative radiopacifiers, material consistency and handling, and the effect of powder-to-liquid ratio (PLR) were all investigated, utilising the model system.

5 wt% Plaster of Paris content was found to provide optimal material characteristics, with Bi_2O_3 the most effective radiopacifier, requiring a minimum proportion of 20 wt% for adequate radiopacity to meet the required standard. A higher PLR (4.0 – 4.5 g/ml) than recommended for commercial MTA was found to be best for cement workability and material properties, including radiopacity.

Dedicated to my grandparents,

all of whom supported my education
in one way or another
– I would not be where I am
now without you.

Education is our greatest opportunity
to give an irrevocable gift
to the next generation.

Dr Ernie Fletcher

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ACRONYMS & ABBREVIATIONS

$BaSO_4$	Barium sulphate
Bi_2O_3	Bismuth oxide
CS	Compressive strength
gMTA[A]	Grey MTA by Angelus® (MTA Angelus® Grey)
gMTA[D]	Grey MTA by Dentsply (ProRoot™) – no longer in production
gMTA[MS]	Grey MTA Model System (75 wt% MC + 20 wt% Bi_2O_3 + 5 wt% POP)
GPPC	General purpose Portland cement
La_2O_3	Lanthanum oxide
MC	Mastercrete (Portland cement)
mmAl	Millimetres of aluminium (the recognised standard for measuring radiopacity)
MS	Model system
MTA	Mineral trioxide aggregate
PC	Portland cement
PLR	Powder-to-liquid ratio
POP	Plaster of Paris (calcium sulphate hemihydrate)
PTFE	Polytetrafluoroethylene
RO	Radiopacifier
RP	Relative porosity
SC	Snowcrete (Portland cement)
Ta_2O_5	Tantalum pentoxide
wMTA[A]	White MTA by Angelus® (MTA Angelus® White)
wMTA[D]	White MTA by Dentsply (ProRoot™)
wMTA[MS]	White MTA Model System (75 wt% SC + 20 wt% Bi_2O_3 + 5 wt% POP)

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1 INTRODUCTION

1.1 The tooth in health and disease

In order to appropriately research and develop a dental restorative material, a sound understanding of oro-dental anatomy, physiology and pathology is required. Although mineral trioxide aggregate (MTA) was initially developed as a 'root-end filling material' for use in the permanent dentition [Torabinejad et al, 1995], its successful application in deciduous teeth has now also been reported [Subramaniam et al, 2009; Ng & Brearley Messer, 2008]. Relevant detail for both the deciduous and permanent dentitions will thus be covered in this introduction .

1.1.1 The tooth in health

Both deciduous and permanent teeth consist of two principal anatomical parts – the crown and root(s). Root number varies depending on the tooth; anterior teeth (incisors and canines) have one root, premolars have one to two roots and molar teeth two to four roots. See Figure 1. The roots sit within alveolar bone and are secured in position by the periodontal ligament. The gingiva is the soft mucosal tissue that covers the alveolar bone and terminates around the cervical (neck) region of each tooth.

Each tooth comprises four distinct tissues – enamel, dentine, cementum and pulp – of which all but pulp are mineralised. Dental enamel is the hardest tissue in the human body and also the most mineralised (approximately 96 wt% inorganic material); the remaining 4 wt% is organic material and water [Nanci, 2013]. Enamel generally remains confined to the crown of the tooth, where its strength is needed to resist occlusal forces and wear. The structure of the majority inorganic body of enamel is composed of hydroxyapatite crystals, that are organised

into rod-like structures (enamel rods), running in columns from the tooth surface to the underlying layer of dental tissue – dentine.

Dentine is a hard mineralised tissue, though not as strong as enamel, that is composed of 70 wt% inorganic hydroxyapatite crystals and 30 wt% organic material (mainly collagen and ground substance) [Nanci, 2013]. As dentine is less mineralised than enamel, it is less brittle and more resilient, forming an ideal supporting structural layer of tissue within the crown and root of a tooth. Dentine is made up of tissue with many fine tubular structures (dentinal tubules), radiating from the underlying dental pulp through to the enamel-dentine interface, called the amelo-dentinal junction [Bath-Balogh & Fehrnbach, 2011]. A layer of highly specialised cells (odontoblasts) sit within the dental pulp, with cellular processes (odontoblastic process) extending within the dentinal tubules; this is called the pulp-dentine complex. When stimulated (i.e. bacterial ingress, dental/occlusal trauma, mechanical, chemical or thermal irritants), the odontoblastic processes affected cause their odontoblasts to secrete more mineralised tissue (reactionary dentine) as part of a natural reparative/maintenance process [Kinneya et al, 2005].

The dental pulp sits within the core of the tooth, beneath the dentine layer, and extends from the crown, down through the root(s) to terminate at the apical foramen. Dental pulp is not mineralised and consists of soft connective tissue made up of cells, a fibrous collagen matrix, ground substance, lymphatic vessels, nerve fibres and fine blood vessels distributed throughout. The cells present within dental pulp consist of undifferentiated mesenchymal cells (which can differentiate into a variety of cells as needed) and include fibroblasts, odontoblasts, lymphocytes, macrophages [Avery & Steele, 2002].

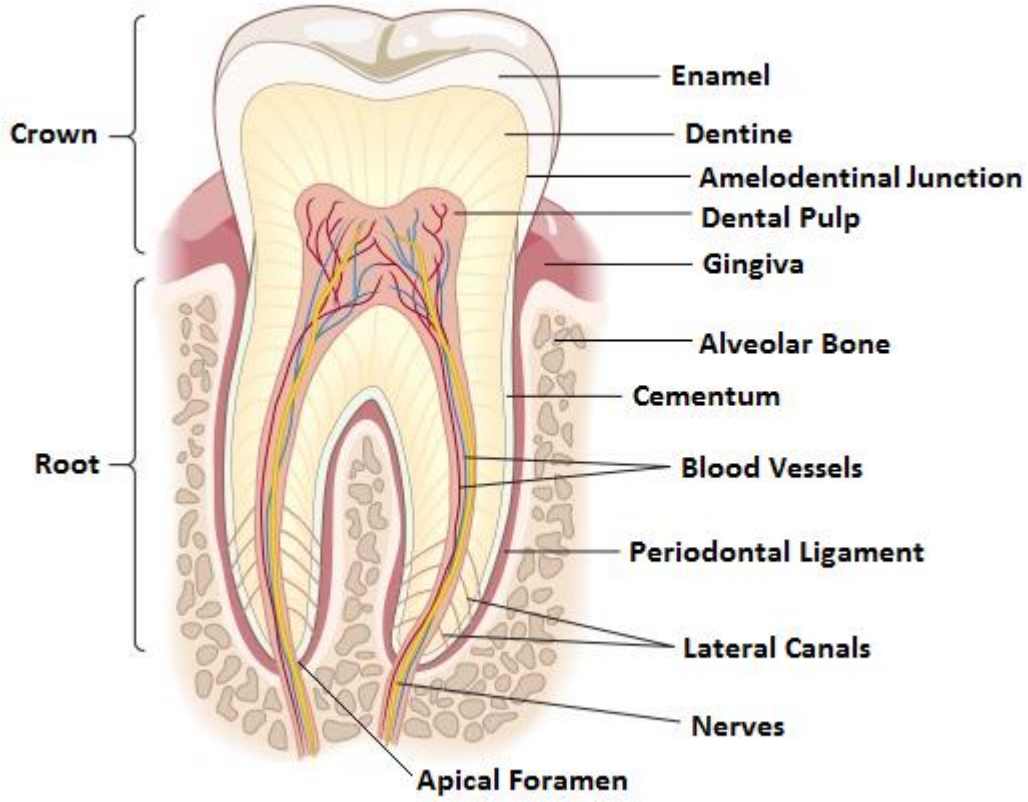

Figure 1: An adapted cross-sectional diagram of a lower permanent molar and its supporting structures. [Encyclopaedia Britannica, 2013]

The final dental tissue to contribute to a tooth's structure is cementum, a mineralised substance that is softer than dentine, covering the surface of roots and extending up to interface with enamel at the cervical region. Cementum is composed of 45-50 wt% inorganic hydroxyapatite crystals and 50-55 wt% organic material (mainly collagen and ground substance) [Nanci, 2013]. Adjacent and within the cementum are cementoblasts and cementocytes – these cells are responsible for the production and maintenance of the cementum layer [Bosshardt & Selvig, 1997]. The periodontal ligament , attached to the adjacent alveolar bone, embeds into the dental cementum to provide support and retention for the tooth within its socket.

A healthy, mature tooth will utilise its component parts to fulfil its functions (i.e. mastication, proprioception, speech), and maintain its structure, integrity and vitality through the deposition of secondary/tertiary dentine and its primarily cell-mediated defence mechanisms [Farges et al, 2015]. Despite the size and morphological differences between deciduous and permanent teeth, research has found that deciduous teeth have similar potential to permanent teeth to mount defensive inflammatory responses, at least to dental caries [Rodd & Boissonade, 2006a].

1.1.2 The tooth in disease

When a tooth sustains sufficient damage from one or more noxious elements/factors (i.e. bacterial ingress, dental/occlusal trauma, mechanical, chemical or thermal irritants), the pulp becomes inflamed and undergoes degenerative changes that may be reversible or irreversible [Goldberg, 2014]. With prolonged and/or significant exposure to irritants, the patient may start to experience symptoms and devitalisation/necrosis of pulpal tissue will eventually occur. Cellular inflammatory changes in the periodontal region around the root (periodontitis) will arise, which could eventually result in a dental abscess. It is from the point that the pulpal tissue becomes irreversibly damaged that root canal treatment or dental extraction should be considered [Cawson, 2008]. The rationale behind root canal treatment is that through the removal of infected pulp tissue, disinfection of the root canal system and adequate sealing/restoration of the canal and tooth, the periodontal tissues supporting the tooth can stabilise/heal, allowing the tooth to return to normal function [Tronstad, 2009].

1.1.3 Endodontic practices prior to the advent of mineral trioxide aggregate

Modern day endodontics includes the study, diagnosis, prevention and management of diseases and injuries of the dental pulp and periradicular tissues [Kohli, 2009; American Dental Association, 2016]. The practice of managing teeth with pulpally-related disorders has significantly evolved over the years , with the development of improved diagnostic/therapeutic equipment, knowledge and materials, like MTA. With the conservative, 'minimally invasive' direction dentistry is starting to take [Banerjee, 2013], MTA has some favourable properties complimentary to this management approach (to be discussed in section 1.2.2). However it should be noted that prior to the introduction of MTA in 1994 [US5415547, 1994], and other similar calcium silicate materials (e.g. Biodentine) subsequently, certain endodontic practices were relatively different , largely due to the materials available at the time. As MTA is discussed in the following section, some past practices will be reflected upon to highlight both the versatility of MTA and the impact it has had on patient care since its introduction.

1.2 Mineral Trioxide Aggregate

Mineral trioxide aggregate (MTA) is a dental restorative cement that has been used in dentistry for just over two decades now [Torabinejad et al, 1995; Pitt Ford et al, 1996]. It was originally developed as a root-end filling material [US5415547, 1994; Torabinejad et al, 1995], though has since been successfully used in perforation repairs [Main et al, 2004], pulp-capping [Pitt Ford et al, 1996], pulpotomies [Peng et al, 2006; Alqaderi et al, 2014], apicectomies [Grossman et al, 2003] and the treatment of non-vital immature permanent teeth through apexification [Witherspoon & Ham, 2001] or the regenerative endodontic technique [Cantekin et al, 2014]. Despite having some negative traits (to be discussed in the following

sections), MTA has revolutionised how dentists practice, especially in the fields of endodontics and paediatric dentistry. Grey and white versions of commercial MTA are available at this time.

1.2.1 Composition

The original grey ProRoot™ MTA comprised approximately 75 wt% Portland cement (PC), 20 wt% Bi_2O_3 and 5 wt% calcium sulphate (gypsum) [MS-1098 (00-08B); 2001]. Bi_2O_3 is a radiopacifier and necessary for radiographic assessment intra-/post-operatively. Calcium sulphate is used as a setting modifier to improve setting time and the short-term hardness of the cement [US5415547, 1994]. White MTA was released a few years later in response to discolouration problems experienced with the grey version; the iron-containing phase (Tetracalcium alumino-ferrite) was removed from the cement in the hope of resolving the problem [Camilleri, 2008c], however this was not the case. It was recently been found that when exposed to sodium hypochlorite (NaOCl), the Bi_2O_3 radiopacifier in MTA gradually discolours to a dark brown colour [Marciano et al, 2015 ; Vovaraityte et al, 2016].

Both the composition and setting reaction of MTA have been found to be similar to Portland cement [Camilleri et al, 2006; de Oliveira et al, 2007,]. The components and setting reactions of Portland cement, both with and without the presence of calcium sulphate, are covered in more detail later in section 1.3.2. Although some debate did exist, it is believed that the Bi_2O_3 radiopacifier does not participate in the hydration reactions of the cement system [Li & Coleman, 2015; Camilleri, 2008c].

1.2.2 Properties

MTA has both favourable and unfavourable properties that need to be carefully considered if selecting to use the material on a patient. Often a balance must be struck between the positive and negative characteristics, thus the operator must have a good understanding of the cement.

Favourable properties of MTA:

Strength: The compressive strength of MTA was found to be around 40MPa initially, after 24 hours setting time, and increased to 67.3MPa after 21 days [Torabinejad et al, 1995]. When compared to other root-end filling materials, MTA's compressive strength was found to be comparable to Super EBA and IRM (Intermediate Restorative Material), though lower than composite resin or amalgam [Torabinejad et al, 1995]. Compressive strength has been used by the Portland cement manufacturing industry as a quality indicator for the durability and longevity of a cement [Committee on Nonconventional Concrete Technologies for Renewal of the Highway Infrastructure, National Research Council, 1997]. Although the compressive strength of a material is an important consideration, MTA is not intended to be placed in heavy load-bearing areas, thus its strength is more than adequate for its intended purpose.

Sets in moisture: Both MTA and Portland cement have been found to set under physiological conditions [Islam et al, 2006] and their setting is uninhibited by water or blood. As MTA contains Portland cement, which is classified as a 'hydraulic cement' (i.e. can set and is stable in the presence of moisture) [Deb, 2015], this is an ideal property for the

intended use of the material. It should be remembered that MTA requires moisture to set, otherwise the physical properties of the material will be compromised [Khalilak et al, 2012].

Marginal adaptation and sealing properties: MTA has been found to provide excellent sealing properties providing it is placed in adequate thickness; a thickness of 3-5mm was found to be sufficient to provide a good seal, and leaked significantly less than other apicectomy/root-repair materials tested (Super EBA, IRM and amalgam) [Torabinejad et al, 1994; Fischer et al, 1998]. Furthermore, a 4mm thickness of MTA has been demonstrated to provide a more effective seal than thinner sections [Valois & Costa, 2004], and is now the minimum thickness that most clinicians work to.

Antimicrobial effect: The pH of mixed MTA has been found to be between 12.1-12.5 at 24 hours setting time, for both commercial MTAs - ProRoot™ and MTA Angelus® [da Silva et al, 2010; Torabinejad et al, 1995]. Calcium hydroxide paste, used in endodontics for many decades, is also associated with a high pH (12.5-12.8), which has been found to have a beneficial bacteriostatic/bacteriocidal effect on the microorganisms in/around the material [Mohammadi et al, 2012]. MTA has also been found to have an antifungal effect when put in close proximity with Candida albicans [Bogen & Kuttler, 2009]. The pH of MTA has been found to decrease over time – 9.7 by day 28 [Abu Zeid et al, 2015] – though this works to the benefit of the surrounding tissue cells which cannot survive for prolonged periods in highly alkaline environments.

Biocompatibility and tissue regenerative effect: MTA has been shown to be biocompatible and have very limited cytotoxic effects on various cells, including human gingival fibroblast cells, periodontal ligament cells and alveolar bone cells [Asgary et al, 2012; Bonson et al, 2004; Tani-Ishii et al, 2007]. When in contact with bone cells, MTA was been found to elicit an initial inflammatory response, though this resolves within a 12-week period with no significantly detrimental effect on the tissues [Sousa et al, 2004]. Koh et al (1997) found that MTA actually stimulated interleukin production and cytokine release to actively promote hard tissue formation. MTA, when placed on exposed vital pulp tissue in dog models, caused no inflammatory response and produced calcium hydroxide, which resulted in the formation of a dentine bridge [Faraco & Holland, 2001]. In an experiment with human pulps, Nair et al, 2009, found MTA to induce a smaller pulpal inflammatory response and more predictable hard tissue barrier when compared to calcium hydroxide liner. Numerous studies have now been published, with significant results, in support of MTA and its favourable and therapeutic tissue response.

Radiopacity: Radiopacity is an essential requirement for endodontic materials, as radiographic assessment of their placement is usually indicated intra- or post-operatively, dependent on the procedure being undertaken. Bi_2O_3 is added to the formulation of MTA to approximately 20 wt% [MS-1098 (00-08B), 2001] to meet the radiopacifier minimum standard that has been set [ISO 6876:2001]. As with Portland cement, MTA is stable and has a low/negligible solubility level once set, thus holding its density (and thus radiopacity) over time [Rao et al, 2009].

Unfavourable properties of MTA:

Setting time: Compared to most other dental materials, MTA has a relatively long setting time and is stated on average to take three to four hours to set, in the presence of moisture [Tait et al, 2005] . Adding extra gypsum to MTA reduces the setting time of the material considerably, though this has been found to compromise the strength of the cement and its marginal integrity [Bramante, 2013]. The newer formulation of MTA Angelus® states an initial setting time of 10 minutes and final set of 15 minutes [CRO-PR4536, 2015] – this most likely has been achieved by increasing the quantity of calcium sulphate in the cement system. It has been shown that an acidic environment (e.g. abscess around the root of a tooth) does not interfere with the setting process of MTA [Roy, 2001].

Workability: The 'workability' of a material is considered to be based on a combination of factors, including its setting time, consistency and how difficult or easy it is to manipulate for its given clinical purpose. MTA is generally considered by clinicians to have a slow working/setting time (see previous point) and is an awkward material to mix and place. Clinicians and nurses who use MTA on a regular basis do develop techniques to manipulate the material more effectively, though the workability and handling properties of MTA are a negative aspect to the cement.

Bond strength: The retentive/bond strength of MTA has been found to be less than zinc phosphate or glass ionomer cements [Vargas et al, 2004]. Fortunately for MTA, it is not normally placed where it is going to be exposed to significant loading or shear forces. The powder-to-liquid ratio that MTA is mixed with has also been found to influence the material

retention, where a PLR of 4.0 g/ml was significantly more retentive than 2.0 g/ml [Turker & Uzunoglu, 2016]. Although a negative attribute to the material, this characteristic does not significantly affect the performance of the cement.

Discolouration: Since its release, clinicians have always been aware of MTA's potential for discolouration. It was initially suspected that the discolouration from MTA was caused by the iron-containing phase (Tetracalcium alumino-ferrite), so this was removed from the cement when white MTA was developed, in the hope of addressing the problem [Camilleri, 2008c]. Unfortunately the discolouration problem persisted and many clinicians ceased using MTA for direct pulp caps and partial pulpotomies in anterior teeth, especially in younger patients, as this cohort of individuals had larger pulp chambers and dentinal tubules in their teeth that seemed to facilitate the movement of discolouration within the tooth. Recent studies have found that when exposed to sodium hypochlorite (NaOCl), the Bi_2O_3 radiopacifier in MTA gradually changes to a dark brown colour [Marciano, 2015 ; Vovaraityte, 2016], which would explain the discolouration in a significant proportion of patients, though not address the patients who have not have NaOCl used on their tooth (e.g. direct pulp cap or partial pulpotomy patients). More research is required in this area to further isolate the causative factors for dental discolouration post-MTA placement.

1.2.3 Clinical applications and limitations

Vital pulpotomy: A vital pulpotomy is the currently accepted method to manage a vital pulpally involved primary tooth, usually a molar, if extraction is intended to be avoided [Rodd et al, 2006b]. The concept of a vital pulpotomy is to amputate the coronal radicular pulp, already inflamed/infected, from the tooth and place a compatible material over the exposed radicular pulp stumps prior to restoring the tooth. Materials used in the past have been formocreosol, zinc oxide eugenol, ferric sulphate and calcium hydroxide, though most of these are pulpal irritants and not very biocompatible. Several studies published have compared MTA with these other materials at the pulp-restoration interface, to find that MTA was more successful in preventing pain and sepsis during the lifetime of the deciduous tooth [Yildiz et al, 2014; Stringhini et al, 2015; Asgary et al, 2014]. MTA is able to induce thick dentinal bridges and preserve the normal pulpal architecture, with minimal inflammatory response, that makes it an ideal material for this procedure [Aeinehchi et al, 2007]. Due to the excellent pulpal response elicited by MTA, some clinicians are now undertaking vital pulpotomies with MTA on permanent molar teeth [Alqaderi et al, 2014]. The only real limitation of using MTA in this situation is the choice of material placed directly on top of it.

Pulp cap: Two classifications of pulp caps exist, and are both placed in vital teeth (deciduous or permanent) to preserve pulpal vitality and try and avoid endodontic treatment. A direct pulp cap is placed directly over a pulpal exposure (that has occurred during cavity preparation or following dental trauma); an indirect pulp cap is placed where the pulp has not been exposed, though the cavity depth of the tooth is very close to exposing the pulp. Indirect pulp caps have been found to have a better long-term pulpal prognosis, than direct pulp caps, though ensuring a well placed material for a pulp cap and an adequately sound restoration is

essential for a good outcome [Hilton, 2009]. Prior to MTA, calcium hydroxide was the favoured material to place, especially for a direct pulp cap. With MTA's superior biological properties, it is now the preferential material to use for a direct pulp cap in either deciduous or permanent teeth [Hilton, 2013; Peng, 2006]. Again, the only real limitation of using MTA in this situation is the choice of material placed directly on top of it.

Partial pulpotomy: This procedure is undertaken in permanent teeth and usually following a traumatic exposure of the pulp. It involves the excision of 2-3 mm depth of pulpal tissue from around the area of exposure, followed by the placement of a biocompatible material over the pulp tissue. Calcium hydroxide has historically been the material of choice for the direct pulp cap in this procedure, though MTA is now considered the better material for this clinical situation, due to its favourable tissue response. The intention of this procedure is to try and provide a good seal and restoration over the exposure and cavity to try and maintain pulpal vitality. Dental discolouration has been reported when MTA was used in this situation [Belobrov & Parashos, 2011]; some clinicians have gone back to the use of calcium hydroxide placement over the pulp in teeth where aesthetics cannot afford to be compromised, especially since reported success rates using calcium hydroxide were also high [Fuks et al, 1993]. There is also the limitation of only being able to place compatible materials on top of the MTA if used here.

Root perforation repair: Root perforations can occur through root resorption, or via iatrogenic or carious means [Azim, 2014]. These repair procedures are only undertaken on permanent teeth, and is where MTA excels, as the materials used for this procedure pre-MTA were far from ideal. Some of the materials used for perforation repairs in the past included amalgam, zinc oxide eugenol cement, gutta percha and glass ionomer cement [Kakani, 2015]. Placing MTA into a root perforation will vary in difficulty depending on several factors, including the position of the perforation, access/visibility, having the appropriate carrier and packer for the material placement, etc. Like with partial pulpotomies, MTA used in this situation in aesthetic areas (particularly if the perforation is relatively superficial) are at risk of causing dental discolouration [Regan, 2005].

Apexification: Only performed in the permanent dentition, this is an artificial root-end closure procedure that is required to be undertaken to retain an immature tooth that has devitalised; through the apexification of the root, the tooth could then be root-filled and restored [Rafter, 2005]. Traditionally, apexification was undertaken through repeated dressing of the tooth with non-setting calcium hydroxide (every 3 months or so) until a calcific apical barrier formed. This was found to weaken the tooth through the repeated re-accessing of the pulp chamber and the prolonged retention of calcium hydroxide within the root canal [Andreasen, 2002; Batur, 2013]. MTA has allowed for a one-visit apical closure procedure, which is beneficial both for the patient and operator, and is associated with a better long-term prognosis for the tooth [Lin et al, 2016]. As with perforation repairs, apexification procedures can vary in difficulty, though are relatively straightforward for the skilled operator with the correct equipment.

Apicectomy: Again, only a procedure undertaken on permanent teeth, to be considered when conventional orthograde root canal treatment has failed. It involves the surgical resection of the infected root apex +/- debridement of the apical tissues prior to the placement of a retrograde root filling prior to closing up the wound. Similar to perforation repairs, historic materials used for this procedure included amalgam, zinc oxide eugenol cement, gutta percha and glass ionomer cement [Grossman, 2003]. Again, with its superior material properties, including seal integrity [Aqrabwi, 2000], MTA is now considered to be the gold-standard filling material for this procedure. The limitation of MTA when used in an apicectomy is that it is being placed in an often moist and bloody environment, thus there is a risk of some superficial wash-out of the material if care is not taken when it is being placed or during wound closure.

Regenerative endodontic technique: Also known as 'root revascularisation'. This is a treatment option for a permanent non-vital immature tooth (usually with very short root length), normally only undertaken on anterior or premolar teeth. The procedure involves disinfecting the canal system of the tooth with antibiotic or calcium hydroxide paste over several weeks, prior to removing the paste and then intentionally agitating the apical tissues with a sharp object to encourage bleeding and a blood clot to form within the canal. An MTA seal is then placed at the cervical level of the tooth (onto the blood clot) and the crown definitively restored. It is thought that stem cells in the apical root canal region are stimulated through the agitation of the apical tissues to then differentiate and continue natural root formation (apexogenesis). Promising results have been seen [Petrino, 2010]. Although MTA is thought to be the ideal material for the seal over the blood clot, it is clinically challenging to place without it sinking into/through the clot. This procedure has also been found to result in unwanted coronal discolouration from the MTA and certain antibiotic pastes [Kahler &

Rossi-Fedele, 2016]. There is also the limitation of only being able to place compatible materials on top of the MTA if used here.

1.3 Portland cement

Portland cement is a hydraulic cement (sets in the presence of water) that is the primary component of MTA [MS-1098 (00-08B), 2001; Camilleri, 2008c] and is what predominantly gives MTA its material characteristics [de Oliveira, 2007]. Aside from the Bi_2O_3 radiopacifier additive, both the grey and white Dentsply ProRoot™ MTAs and the MTA Angelus® cements were found to have very similar constituent elements to Portland cement [Song et al, 2006; Camilleri et al, 2005; Funteas et al, 2003; Oliveira et al, 2007]. Thus to understand MTA , Portland cement as a material, and its reactions, need to be comprehended.

1.3.1 Manufacturing

Portland cement is made from sintering (heating materials to the point where they coalesce into a mass without liquefaction) a mixture of ground aluminosilicate ($2SiO_2.Al_2O_3$; clay or shale), calcium carbonate ($CaCO_3$; chalk or limestone), iron (III) oxide (Fe_2O_3; ferric oxide) and silicone dioxide (SiO_2; silica sand) in a special kiln at temperatures of 1400-1600^oC, to form a clinker [Bye, 1999; Taylor, 2004]. See Table 1 for the proportions of each main constituent part that is combined to produce Portland cement clinker [Singh et al, 1992].

Table 1: The principal component materials needed for the production of clinker, when manufacturing Portland cement.

Principal anhydrous components used to make Portland cement clinker	Chemical Formula	wt%
Calcium oxide (lime)	CaO	60-70
Silicone dioxide (silica)	SiO_2	20-25
Aluminium oxide (alumina)	Al_2O_3	5-7
Iron (III) oxide	Fe_2O_3	3-5

Once formed, Portland cement clinker consists of four primary mineral phases: tricalcium silicate (alite), dicalcium silicate (belite), tricalcium aluminate, calcium alumina ferrite, and approximately 5 wt% alkali sulphates and impurities [Gani, 1997]. See Table 2 below.

Table 2: The predominant mineral phases found in Portland cement clinker, comprising approximately 95 wt% of the material. The remaining 5 wt% is composed of alkali sulphites and impurities

Anhydrous Mineral Phase	wt%	Chemical Formula	Abbreviation
Tricalcium silicate (Alite)	65	$3CaO.SiO_2$	C_3S
Dicalcium silicate (Belite)	15	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	7	$3CaO.Al_2O_3$	C_3A
Tetracalcium alumino ferrite	8	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF

The Portland cement clinker is then finely ground up and mixed with approximately 5 wt% calcium sulphate (usually gypsum) to control the early hydration reactions [Klieger & Lamond, 1994], in the final cement product. Portland cement is usually grey in colour, though white versions do exist and are produced through keeping Fe_2O_3, Mn_2O_3 and Cr_2O_3 levels as low as possible in the raw materials used, and increasing the ratio of Al_2O_3 to Fe_2O_3 in the clinker [Taylor, 2004] .

Table 3: The ASTM C150 standards description of Portland cements. Additional types of Portland cements exist, though these are blended and specified by a different set of standards

Cement Type	Description
I	**Normal** (a general purpose Portland cement, where special properties are not required; susceptible to sulphites and has a greater exothermic reaction on hydration)
II	**Moderate Sulphate Resistance with Moderate Heat of Hydration** (slower rate of reaction to keep heat generated to a minimum; for large mass structures with some sulphite exposure)
III	**High Early Strength** (for when structures need to be put into service very quickly)
IV	**Low Heat Hydration** (for very large structures requiring a slow rate of set for strength; eg. large gravity dams)
V	**High Sulphate Resistance** (for exposure to high sulphate soils or groundwater)

The composition of Portland cement can be altered through the modification of the raw materials used, variation in production methods (ie. temperatures used, milling technique and additives included), and are now governed by various industry standards around the world (ASTM C150, 2005 ; BS EN 197-1, 2000). The Portland cement used in the commercial MTA is Type I [US5415547, 1994; Camilleri, 2008c]. See Table 3 for the American Society for Testing and Materials (ASTM) C150 standards description.

1.3.2 Hydration reactions

There are multiple reactions that occur with the setting of Portland cement, though the two main reactions are associated with the majority calcium silicate phases: alite (tricalcium silicate; C_3S) and belite (dicalcium silicate; C_2S), that make up over 80 wt% of the cement system [Stein & Stevels, 1964; Ramachandran, 1995].

Alite (C_3S) reaction:

$$2(3CaO.SiO_2) + 6H_2O \rightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)_2$$

(tricalcium silicate) + (water) → (calcium silicate hydrate) + (calcium hydroxide)

Belite (C_2S) reaction:

$$2(2CaO.SiO_2) + 4H_2O \rightarrow 3CaO.2SiO_2.3H_2O + Ca(OH)_2$$

(dicalcium silicate) + (water) → (calcium silicate hydrate) + (calcium hydroxide)

The products from these reactions are a rigid calcium-silicate-hydrate gel (C-S-H) and calcium hydroxide. The alite is the most important phase for cement strength in the first

month, as it has a more rapid reaction; belite has a slower reaction and contributes to the overall long-term strength and integrity of the cement [Taylor, 2004]

There is a limited amount (5wt% approximately) of calcium sulphate (gypsum) added to the system during the manufacture of Portland cement [Klieger & Lamond, 1994]; this has been found to only influence the hydration reactions of the two minor phases of Portland cement – tricalcium aluminate and calcium alumina ferrite, which both compete for the calcium sulphate [Camilleri, 2007].

With regard to the tricalcium aluminate phase, two potential reactions can occur. The reaction without calcium sulphate forms calcium aluminate hydrate, which provides rapid hardening of the paste, though with negligible increase in strength [Taylor, 2004]. The reaction with calcium sulphate forms a hydrous calcium aluminium sulphate mineral, called ettringite, which has been found to contribute to very early cement strength and stability (within hours of mixing the cement) [Tokyay, 2016; Taylor, 2004].

Tricalcium aluminate (C_3A) reaction (with no $CaSO_4$):

$$3CaO.Al_2O_3 + Ca(OH)_2 + 12H_2O \rightarrow 4CaO.\ Al_2O_3.13H_2O$$

(tricalcium aluminate) + (calcium hydroxide) + (water) → (calcium aluminate hydrate)

Tricalcium aluminate (C_3A) reaction (with $CaSO_4$):

$$3CaO.Al_2O_3 + 3CaSO_4.2H_2O + 26H_2O \rightarrow 6CaO.\ Al_2O_3.3SO_3.32H_2O$$

(tricalcium aluminate) + (gypsum) + (water) → (ettringite)

Similarly, the other minor phase in the cement – calcium alumino ferrite – has two potential reactions to undergo. The reaction without calcium sulphate forms calcium aluminoferrite hydrate, which has a negligible effect on the cement system; the reaction with calcium sulphate produces calcium sulphoaluminate, which can increase the setting time of the cement system [Taylor, 2004].

Calcium aluminoferrite (C_4AF) reaction (with no $CaSO_4$):

$$4CaO.Al_2O_3.Fe_2O_3 + 2Ca(OH)_2 + 14H_2O \rightarrow$$

(calcium aluminoferrite) + (calcium hydroxide) + (water)

$$4CaO.\ Al_2O_3.Fe_2O_3.13H_2O + Al_2O_3/Fe_2O_3.3H_2O$$

(calcium aluminoferrite hydrate) + (aluminium or iron hydroxide)

Calcium aluminoferrite (C_4AF) reaction (with $CaSO_4$):

$$4CaO.Al_2O_3.Fe_2O_3 + CaSO_4.2H_2O + 16H_2O \rightarrow$$

(calcium aluminoferrite) + (gypsum) + (water)

$$Ca_4(AlO_3/FeO_3)_2(SO)_4.12H_2O + Al_2O_3/Fe_2O_3.3H_2O$$

(calcium sulfo-/ferrous aluminate hydrate) + (iron or aluminium hydroxide)

Portland cement is a complex system made up of multiple hydration reactions that are simultaneously occurring, some of which are in competition with each other (see Figure 2). As the reactions progress, the cement shifts from the ‘setting’ stage to the ‘hardening’ (or maturing) stage, which can continue on for several months.

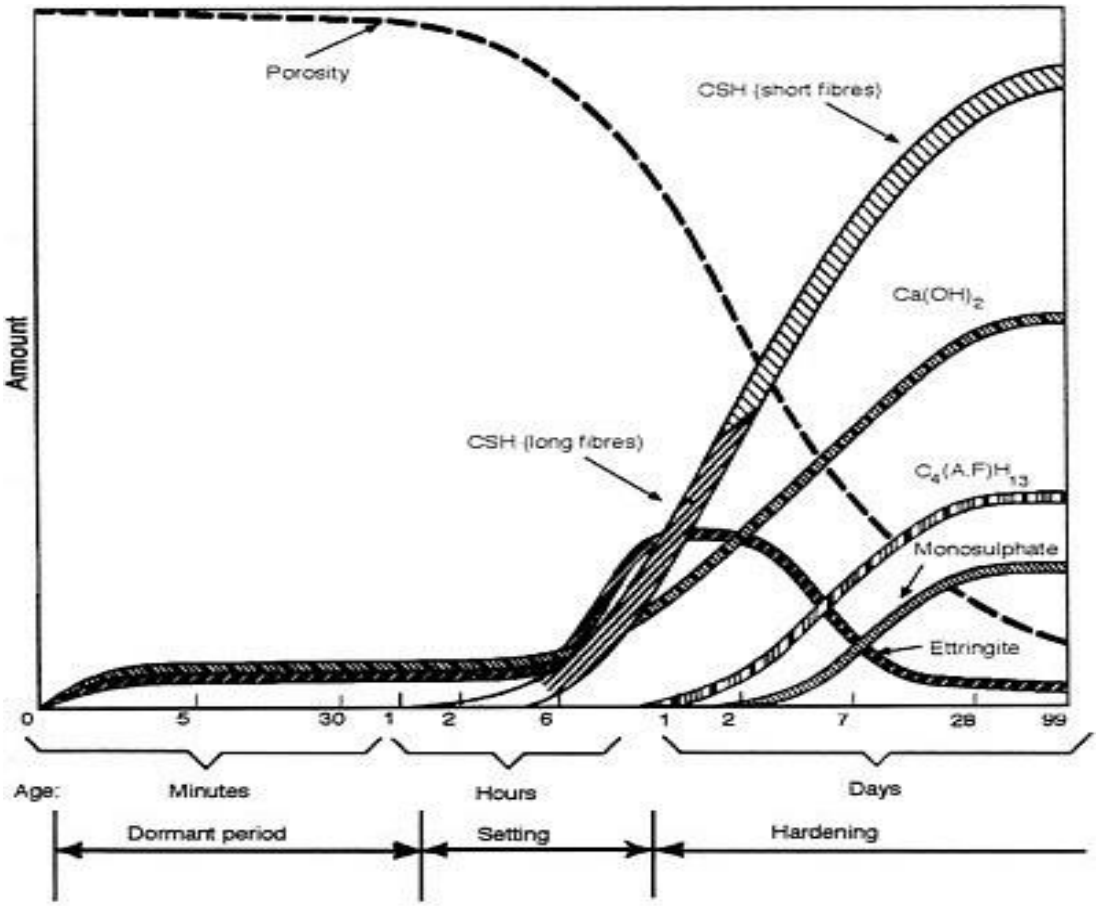

Figure 2: An adapted drawing by Locher and Richartz, printed in Soroka in 1979, explaining the 5 phases of Portland cement paste as a function in time

1.3.3 Characterisation and testing

Several tests were chosen for the characterisation and analysis of the cements made during this project: setting times, compressive strength, relative porosity, apparent and specific densities and radiopacity. All tests, except for radiopacity, are used by the Portland cement industry as quality indicators for cement systems [Committee on Nonconventional Concrete Technologies for Renewal of the Highway Infrastructure, National Research Council, 1997], and felt to be appropriate for the research undertaken. Moreover, compressive strength was a recognised test applied to dental materials and had been used for the initial development of ProRoot™ MTA [Torabinejad, 1995].

As radiopacity had a standard developed for it [ISO 6876:2001] and was an area intended for investigation, it was included to the list of material tests to be undertaken for this PhD.

1.4 The other components of MTA

Though Portland cement makes up the majority component of MTA cement (75 wt%), it is mixed with two other additives that serve important, yet distinct purposes – bismuth oxide and calcium sulphate. An understanding of bismuth oxide and calcium sulphate is just as important as an appreciation of Portland cement, to be able to effectively undertake this research and optimise the material.

1.4.1 Bismuth oxide

Bismuth oxide (Bi_2O_3) is a yellow, thermally stable, highly insoluble compound that is used in the glass and ceramic industry, and has also been found to have applications in dentistry since its use in MTA [Torabinejad, 1995]. Although suspected by some clinicians and scientists to participate in the hydration reactions of MTA, evidence seems to support the contrary [Li & Coleman, 2015; Camilleri, 2008c]. Bismuth oxide, though an essential additive to ensure the radiopacity of MTA cement [US5415547, 1994], has been associated with decreasing the mechanical stability of the cement [Coomaraswamy et al, 2007] and contributing to the discolouration that has been associated with MTA [Marciano et al, 2015].

1.4.2 Calcium sulphate

Calcium sulphate is a white, inorganic compound which exists in three different states (levels of hydration): anhydrous calcium sulphate ($CaSO_4$); calcium sulphate hemihydrate, or Plaster of Paris ($CaSO_4(H_2O)_{0.5}$); calcium sulphate dihydrate ($CaSO_4(H_2O)_2$), or gypsum. Calcium sulphates have been used for medical and dental applications for many years with varied applications [Thomas et al, 2005]; they have also found uses in the industries of building and construction, agriculture and art, to name but a few. When added to MTA, calcium sulphate acts as a setting accelerator which helps improve the handling of the cement [O'Beirne, 2010]; as calcium sulphate concentration is increased in a cement, the solubility increases and mechanical properties decrease proportionately [Low, 2015].

1.5 Aims of the project

Due to the high cost of commercial MTA, and that modifications could not be made to the material for research and development purposes, because of its set formulation, the initial aim of this project was to create and validate an affordable MTA-like model system. Prior to the commencement of this project, there were no published instances of the use of an MTA-like model system in the scientific literature. However studies involving plain Portland cement as a comparison to MTA were first evident as early as 1999 [Wucherpfennig & Green, 1999]. Although the model described in this thesis had been developed by mid- 2005, it was only first described in a research paper in 2007 [Coomaraswamy et al, 2007]. This was also the first year a paper was published by a group of researchers who had attempted to modify commercial MTA (ProRoot™) to improve its characteristics [Ber et al, 2007]. (As an aside, Ber et al cited our 2007 paper and used it as a comparison to discuss their findings.

This marked the beginning of the many publications to follow, on modified commercial MTA cements and MTA-like model systems started by our two groups).

With the development of the model system complete, it was next intended to use it to systematically analyse MTA cement, by modifying its various component parts, with a focus mainly on changes in the physical properties (setting times, compressive strength, relative porosity, apparent and specific densities and radiopacity), so to improve our understanding of MTA and try to optimise the system further where possible. All the component parts of MTA (Portland cement, Bi_2O_3 and calcium sulphate) were to be isolated and assessed for their effect on the cement system, and the proportions needed for an MTA with the best possible properties.

During the course of the research undertaken, it was found that the Bi_2O_3 radiopacifier had a significant and detrimental effect on the cement integrity. Some time was thus spent to investigate other radiopacifiers in the hope of identifying a better alternative for Bi_2O_3.

To conclude the study, it was intended that the manipulation and workability of the MTA-like system was investigated, in parallel with the physical properties. The manipulation and workability of MTA is relatively subjective and can be quite variable between individuals. It was the intention to see how an operator's mix and perception of the material correlated to the optimal mixing ratio and physical properties for the cement system.

2 MATERIALS AND METHODS

2.1 Sample production

Commercial mineral trioxide aggregate is both relatively costly (£40-50 per gram) and comprises a set formulation individual to its type (i.e. grey or white) and manufacturer. For this reason, it was necessary to create an MTA-like cement model system, to allow for modifications in composition and make experimentation with the material financially viable. At the time, an experimental MTA-like model system of this sort had not been devised or recorded in published scientific literature. The original composition for commercial MTA – ProRoot™ (Dentsply Tulsa Dental, Tulsa, USA) - was chosen for the cement model system. The dental cement constituted of 75 wt% Portland cement, 20 wt% Bi_2O_3 and 5 wt% gypsum.

All the cements investigated for the primary component of the model system, Portland cement, were sourced from Blue Circle Industries (LaFarge Aggregates & Concretes, Leicester, UK). Three different cements were available: General Purpose Portland Cement (GPPC), Mastercrete (MC) and Snowcrete (SC). SC was a white Portland cement; GPPC and MC were grey, just like the commercial MTA at that time. MC was ultimately selected for use in the model system, due to its cement type and optimal properties. Bi_2O_3 (Acros Organics, Loughborough, UK) was added to the formulation as a radiopacifier, and plaster of Paris (POP), or calcium sulphate hemihydrate (Crystacal R Plaster, BPB Formula, Newark, UK) as a setting accelerator. The proportions of all three constituents could thus be modified depending on the cement formulation required.

2.1.1 Powder formulation

All powder constituents were weighed out proportionally with a micro-weighing scale and sieved (Endecotts Laboratory Test Sieves, Endecotts Ltd, London, UK) with an aperture size of 250 μm (to remove powder agglomerates), prior to use. This ensured an even particle size distribution throughout the cement and the removal of unwanted agglomerates (that would have introduced flaws to the cement system). The three component powders were varied in amount to allow for the desired experimental cements, however the baseline model system had its formulation closest to the commercial MTA, with 75 wt% Portland cement, 20 wt% Bi_2O_3 and 5 wt% Plaster of Paris (anhydrous calcium sulphate).

2.1.2 Cement paste preparation

All cement powders were hand-mixed with distilled water, to their required powder-to-liquid ratio (PLR), ranging from 2.0 – 5.5 g/ml. The cement was thoroughly mixed, for approximately 60 seconds, to a homogeneous consistency, prior to packing into an appropriate mould.

2.1.3 Production of samples for analysis – mechanical testing

The mixed cement pastes for mechanical testing were packed into custom-made cylindrical polytetrafluoroethylene (PTFE) split moulds (6 mm diameter, 12 mm high), stored for 6 hours at 37^{o}C until initially set, then subsequently removed. Cement samples were then placed into double-distilled deionised water at 37^{o}C for 10 days, simulating the moisture and

temperature MTA is exposed to once placed into a tooth, prior to mechanical testing. A storage duration of 10 days was chosen based on initial experimentation when first setting up the model system – see 'Establishing an experimental MTA-like model system' in section 2.3 for more detail.

2.1.4 Production of samples for analysis – radiopacity testing

The mixed cement pastes for radiopacity testing were packed into custom-made glass slide moulds (10 mm diameter, 1 mm high), to form cement discs, as specified for radiopacity testing according to the ISO standard for dental root canal sealing materials [ISO 6876:2001]. Discs were stored for 6 hours at 37^{o}C until initially set, followed by their immediate radiopacity testing.

2.2 Cement characterisation

2.2.1 Setting time

The Gillmore needle test is an established method to measure the setting times (initial and final set) of both building and dental cements [Braden et al, 1997], and is still used in the ISO standard for dental water-based cements [ISO 9917-1:2007]. The test works on the principle of periodically applying two differently weighted, flat-ended Gillmore 'needles' of varied diameters (large and small), to a setting cement, until neither are able to mark the cement surface with an indentation mark. The 'initial set' is when the lighter, larger diameter needle no longer marks the cement test blank; 'final set' is when the heavier, finer diameter needle no longer marks the sample.

A 24-well (15.6mm diameter, 3.4ml volume), flat bottom, polystyrene cell culture plate (Corning Costar, Sigma-Aldrich, Missouri, USA) was used to form and secure the cement test samples. Test samples were made (n = 2) for all setting raw materials (POP, GPPC, MC, SC), model systems (comprising 75 wt% PC, 20 wt% Bi_2O_3 and 5 wt% POP) made with all 3 PCs, high-PC-content model systems (comprising 85 wt% PC, 10 wt% Bi_2O_3 and 5 wt% POP) made with all 3 PCs, and 4 MTA-like cements with varying concentrations of POP (5 wt%, 10 wt%, 20 wt%, 30 wt%; Bi_2O_3 content constant at 20 wt%; MC used as the PC). All of the aforementioned cement pastes were made of a PLR of 3.0 g/ml; additional test samples (n = 2) were also made of the model system (using MC as the PC) to PLRs of 2.0, 4.0 and 5.0 g/ml, to investigate the influence PLR has on cement setting time. Only two samples were made for each test group as minimal inter-sample variation was expected. 8g of each cement powder was formulated, water added appropriately and mixed for 60 seconds prior to being placed into the corresponding wells and vibrated to ensure a flat setting surface. The samples were then tested with the Gillmore needle apparatus (Gilson Inc., Middleton, USA) every 5 minutes for the first 90 minutes, followed by every 30 minutes until all cements had reached their ‘final set’. The ‘initial set’ needle (2.12mm diameter, 113.4g) was first used on all samples, until it no longer marked their setting surface, and the time recorded at this point; the thinner/heavier ‘final set’ needle (1.06mm diameter, 453.6g) was then used to determine when all cement samples had completed their setting. The cement samples were covered by the plate cover in between testing to prevent dehydration of the samples.

2.2.2 Compressive strength

Compressive strength (CS) is recognised as a quality indicator for a cement system and a gauge for its long-term integrity [Bye, 1999], also used in industry standards (ISO-

RILEM R679:1968; ASTM C39/C39M-16:2016). Cement samples (n ≥ 7 for each variation) were removed from their water-filled storage containers, weighed and had their dimensions recorded . The breaking load of each wet sample was then measured on a Universal Testing Machine (crosshead speed: 1mm/min; Instron 5544, Instron Ltd., HighWycombe, UK). Wet CS was determined to take solubility effects in a moist environment into account and calculated using the equation:

$$\mathrm{CS} = \frac{L}{A} = \frac{L}{\pi \cdot \left(\frac{d}{2}\right)^2}$$

CS	= compressive strength (MPa)
L	= load (N)
A	= cross-sectional area of sample (cm^2)
d	= diameter (cm)

2.2.3 Density and relative porosity

To calculate the relative porosity of the cement system, the apparent wet, dry and strut densities need to be calculated. The apparent wet density of the cement samples was calculated using the equation:

$$\rho_{\mathrm{wet}} = \frac{w_{wet}}{\pi \cdot \left(\frac{d}{2}\right)^2 \cdot h}$$

ρ_{wet}	= apparent wet density (g/cm^3)
w_{wet}	= wet weight (g)
d	= diameter (cm)
h	= height (cm)

Prior to calculating the apparent dry density, the dry sample weight had to be determined. This was measured by choosing out the largest sample fragments following compressive strength testing, placing these in a desiccator and allowing them to sufficiently dry out. These samples were left for 7 days in a desiccator and weighed to ensure they had reached their equilibrium weight and end-point of dehydration. Once the dry sample weight had been found, its apparent dry density was calculated using the equation:

$$\rho_{\text{dry}} = \frac{w_{dry}}{w_{wet}} \times \rho_{\text{wet}}$$

ρ_{dry}	= apparent dry density (g/cm^3)
w_{dry}	= dry weight (g)
w_{wet}	= wet weight (g)
ρ_{wet}	= apparent wet density (g/cm^3)

Sample strut densities (i.e. density of a material without any air voids or flaws) were obtained using helium pycnometry (10 measurements; Accupyc 1330, Micromeritics, Norcross, USA) on the larger fractured pieces collected after the compressive strength testing. With the apparent wet, dry and strut densities determined, the relative porosity (RP) of the samples could be calculated using the equation:

$$RP = 1 - \frac{\rho_{dry}}{\rho_{strut}}$$

RP	= relative porosity (%)
ρ_{dry}	= apparent dry density (g/cm^3)
ρ_{strut}	= strut (specific) density (g/cm^3)

2.2.4 Radiopacity

Radiopacity testing was performed according to the ISO standard for dental root canal sealing materials (ISO 6876:2001). Samples were placed on to an occlusal film (Kodak Insight Dental Film, F/E speed; Kodak, Bagnilet Cedex, France) adjacent to a standard aluminium stepwedge (11-step; Everything X-ray, Princes Risborough, UK) and exposed to 60kV X-rays (7mA; Siemens Heliodent DS X-ray machine; Sirona, Bensheim, Germany) at 30cm focus-film distance. Exposed films were developed in an automatic developing machine (Intra-X; Velopex, Medivance Instruments Ltd., London, UK). See Figure 3.

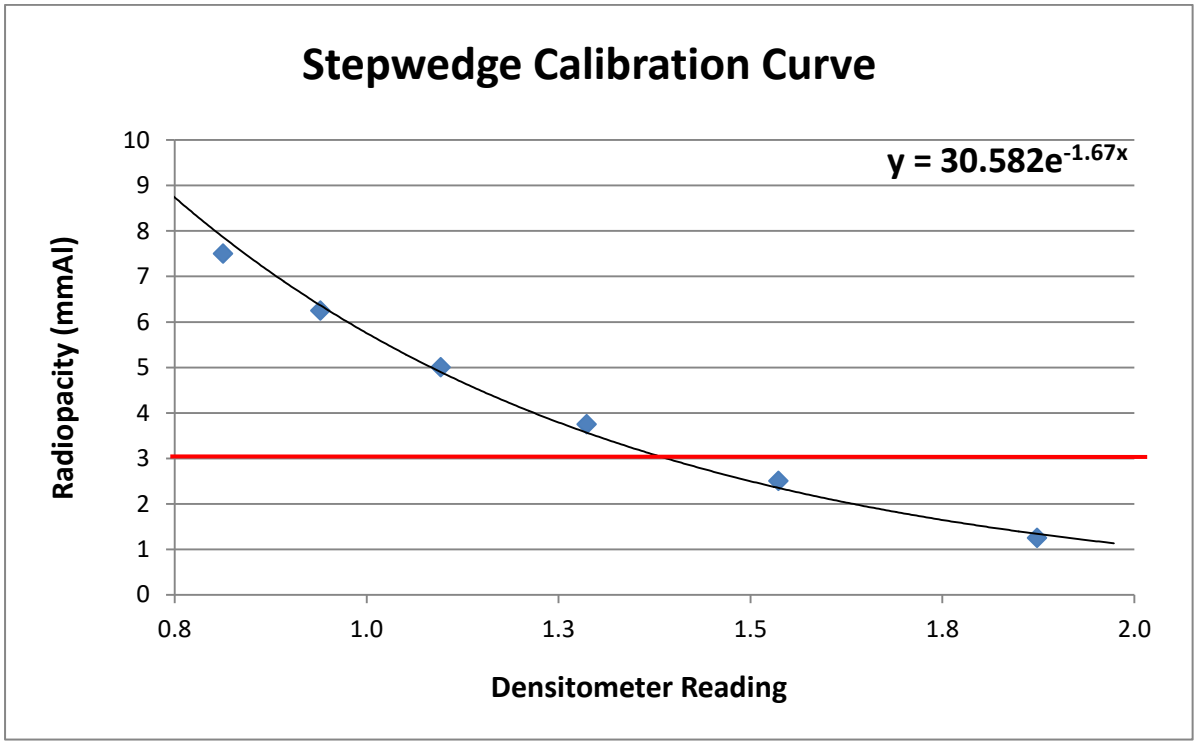

Figure 3: A calibration curve plotted from densitometer readings of a known-thickness aluminium stepwedge. Software was used to calculate an equation to the line of best fit and then used to convert sample results. The red line marks the 3 mmAl minimum standard for dental root canal sealing materials (ISO 6876:2001)

Optical density readings were recorded using a portable transmission digital densitometer (X-Rite 331 B/W Trans-densitometer; X-Rite Inc., Michigan, USA) and converted to equivalent millimetres of Aluminium (mmAl) using Microsoft Excel (Excel 2010, Microsoft Corporation, Redmond, USA). This was done by plotting the densitometer values for each step of the first 6 steps of the aluminium stepwedge (1.25mm thick) that could fit on the film, to create an exponential curve; the software was then used to calculate the formula to the curve, and the formula subsequently used to convert the densitometer readings for the samples tested to the equivalent values of mmAl.

2.3 Establishing an experimental MTA-like model system

2.3.1 Selection of Portland cement for model system

Setting time was initially used to assess the most suitable PCs for the model system. As MC and SC were the premium Portland cements commercially available at the time, and had a faster setting time than GPPC, they were both further assessed for use in the experimental model system. MTA-like cements were formulated using 75 wt% MC or SC, 20 wt% Bi_2O_3 and 5 wt% Plaster of Paris, and tested as described in 2.2.1 – 2.2.3. Both cements were mixed to PLRs of 3.0 and 4.0 g/ml, and stored for 10, 21 and 35 days, prior to CS testing and the calculation of cement RP. CS, density and RP were used to decide which Portland cement was the most suitable for the intended experimental model system.

2.3.2 Establishing sample storage duration for cement testing

Once the model system was developed, batches of samples were made and stored as described in 2.1.3 for 7, 10, 21 and 35 days to determine if storage time had a significant effect on the cement being tested. Within the cement industry, 28 days is the arbitrary recommended period to store a sample prior to compressive strength testing [BS 4550-3.4:1978], though a shorter storage time was preferred due to the large number of sample batches being made. However if left for too short a period, cement integrity may be compromised by an inadequate set, resulting in a higher RP and lower CS. CS, density and RP were again used to characterise the model system stored for different durations.

2.4 Evaluation of different radiopacifiers for an MTA-like cement

Various radiopacifiers were investigated for use with the model system: bismuth oxide (Bi_2O_3; Acros Organics, Loughborough, UK), barium sulphate ($BaSO_4$; Sigma-Aldrich, Missouri, USA), lanthanum oxide (La_2O_3; Sigma-Aldrich, Missouri, USA), and tantalum pentoxide (Ta_2O_5; Sigma-Aldrich, Missouri, USA). These compounds were selected for their higher density and inert nature. Cements were mixed consisting of 75 wt% MC, 5 wt% Plaster of Paris and 20 wt% radiopacifier. Samples were prepared as described in 2.1.1. – 2.1.3, prior to the testing of their mechanical properties (see 2.2.2 – 2.2.3). Radiopacity testing samples were prepared as outlined in 2.1.4 and tested as described in 2.2.4. Commercial grey MTA (ProRoot™, Dentsply, Tulsa Dental, Tulsa, USA) was used as a control.

2.5 The effect of bismuth oxide on an MTA-like cement

Cement samples were made with varying proportions of Bi_2O_3 (0 wt%, 10 wt%, 20 wt%, 30 wt%, 40 wt%) to test the effect the addition of the radiopacifier had on the model cement system. As the Plaster of Paris concentration remained constant at 5 wt%, it was the amount of MC that varied accordingly to the Bi_2O_3. Samples were prepared as stated in 2.1.1 – 2.1.3 and CS, density and RP were assessed as described in 2.2.2 – 2.2.3. Commercial grey MTA (ProRoot™, Dentsply, Tulsa Dental, Tulsa, USA) was used as a control.

2.6 The effect of PLR on the workability of an MTA-like cement

The 'workability' of the cement paste was assessed by rating two characteristics in a blind test: 'consistency' and 'handling'. Consistency is the degree of firmness and viscosity of the mixed paste, and handling is the ability to manipulate and place the cement, from an operator's perspective. Samples for mechanical testing were prepared as outlined in 2.1.1 – 2.1.3, with CS, density and RP being tested as stated in 2.2.2 – 2.2.3.

2.6.1 Selection and blinding of participants

Five specialist dental clinicians, all regular users of MTA, participated in the workability assessment test. The MTA model system was hand-mixed with distilled water to PLRs of 3.0, 3.5, 4.0, 4.5, 5.0 and 5.5 g.ml. Three samples of each PLR were randomly presented to each clinician for rating (1g powder per sample; also testing the consistency of their judgement). The clinicians could not see the proportion of water being mixed with the powder and were only given the cement sample to assess once fully mixed through.

2.6.2 Instructions to participants and data collection

A proforma was developed for the participating clinicians to record their assessments of each cement sampled. Consistency was rated on a scale of 1 to 5, with 3 being set as the ideal cement paste consistency; 1 being too liquid and 5 being too dry. Handling was rated on a scale of 1 to 5, with 5 being a paste of perceived optimum handling, and 1 resembling an unworkable paste. Participants were asked to base their opinions on their own experience with MTA and preference with the material at the time of testing.

2.7 The effect of dilution on the radiopacity of MTA

Four commercial MTA cements (Dentsply ProRoot™ grey MTA, gMTA[D]; Dentsply ProRoot™ white MTA, wMTA[D]; Angelus® grey MTA, gMTA[A]; Angelus® white MTA, wMTA[A]) were tested in this study, along with the model system, for comparison. Each cement was mixed at different PLRs representing various levels of dilution (2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5g/ml; n=9). Samples were prepared as described in 2.1.1, 2.1.2 and 2.1.4, and subjected to radiopacity testing as outlined in 2.2.4. Mechanically tested samples were prepared as stated in 2.1.1 – 2.1.3, and tested as specified in 2.2.2 – 2.2.3.

2.8 Statistical analysis of experimental results

To test the significance of the mean values, a one-way ANOVA was performed on the raw data, followed by a Tukey post hoc test with SPSS 10.0.0 for Windows (SPSS Inc, Chicago, USA). The level of significance P was set at 0.05. Linear regression correlations analyses, also using SPSS 10.0.0 for Windows, were used to obtain best-fit relationships

between RP, dry density, strut density, CS and Bi_2O_3 content, when investigating the effect of Bi_2O_3 on an MTA-like cement.

With the experimentation on effect of PLR on the workability of an MTA-like cement, the significance of the consistency and handling scores were analysed with Kruskal-Wallis and Mann-Whitney tests, using Minitab release 14 for Windows (Minitab Inc., State College, USA). Significance of the non-parametric data was set at $p < 0.01$.

3 RESULTS

3.1 Establishment of an experimental MTA-like cement model system

Setting times (of component materials and experimental cement mixes), sample storage duration, POP content and variations in powder-to-liquid ratios were investigated to determine suitable formulation of a model system to be used for the further stages of this research project.

3.1.1 Setting times of raw materials

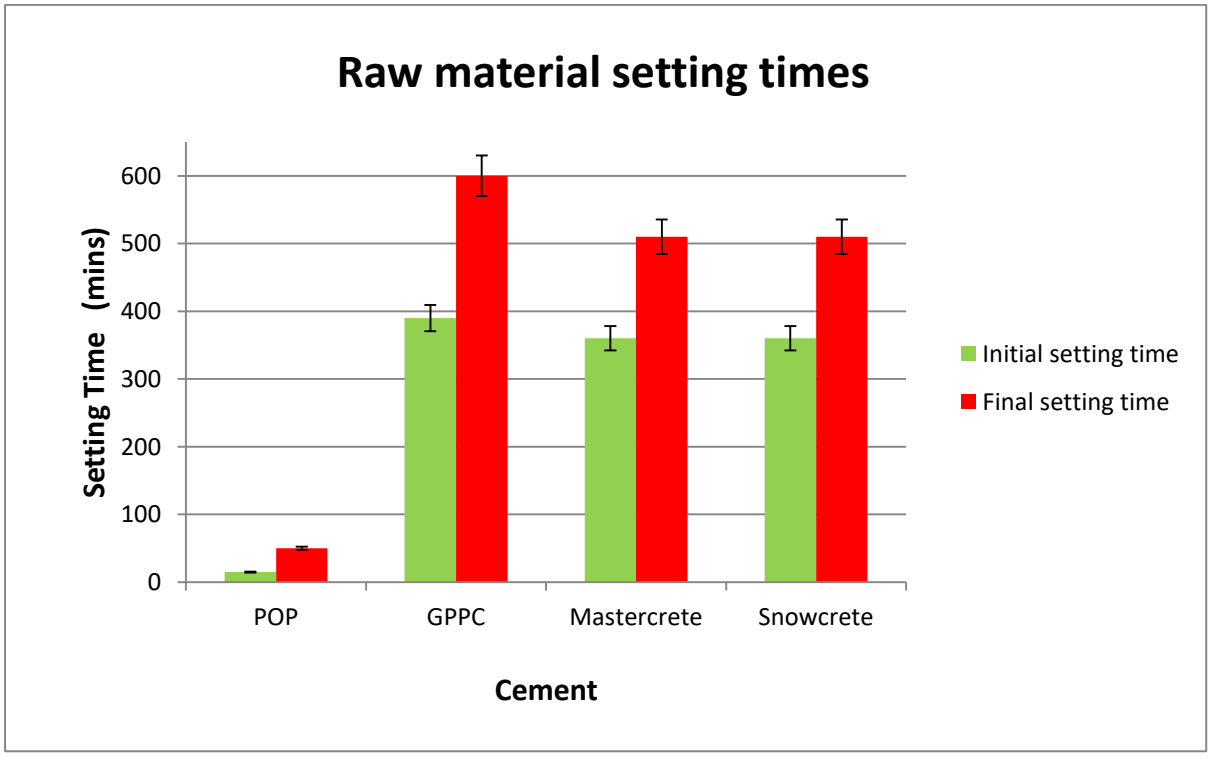

Figure 4: The setting times of the raw materials for the model system, measured using a Gillmore needle apparatus. Both 'initial' and 'final' setting times were recorded. All materials were mixed to a PLR of 3.0 g/ml. POP was significantly different to the other groups ($p < 0.01$); GPPC final setting time was significantly different to Mastercrete and Snowcrete ($p < 0.05$).

The raw materials being considered for use in the model system were three types of Portland cement, General Purpose Portland Cement [GPPC], Mastercrete [MC] and Snowcrete [SC], and as a comparison and additive, Plaster of Paris [POP]. All were mixed to a PLR of 3.0 g/ml. As expected, POP had the shortest setting time of all the materials (15 mins initial set; 50 mins final set). Of the Portland cements, both MC and SC had identical setting profiles (360 mins initial set; 510 mins final set). GPPC took slightly longer to set, with an initial setting time of 390 mins, and final setting time of 600 mins. See Figure 4.

3.1.2 Setting times of various PCs

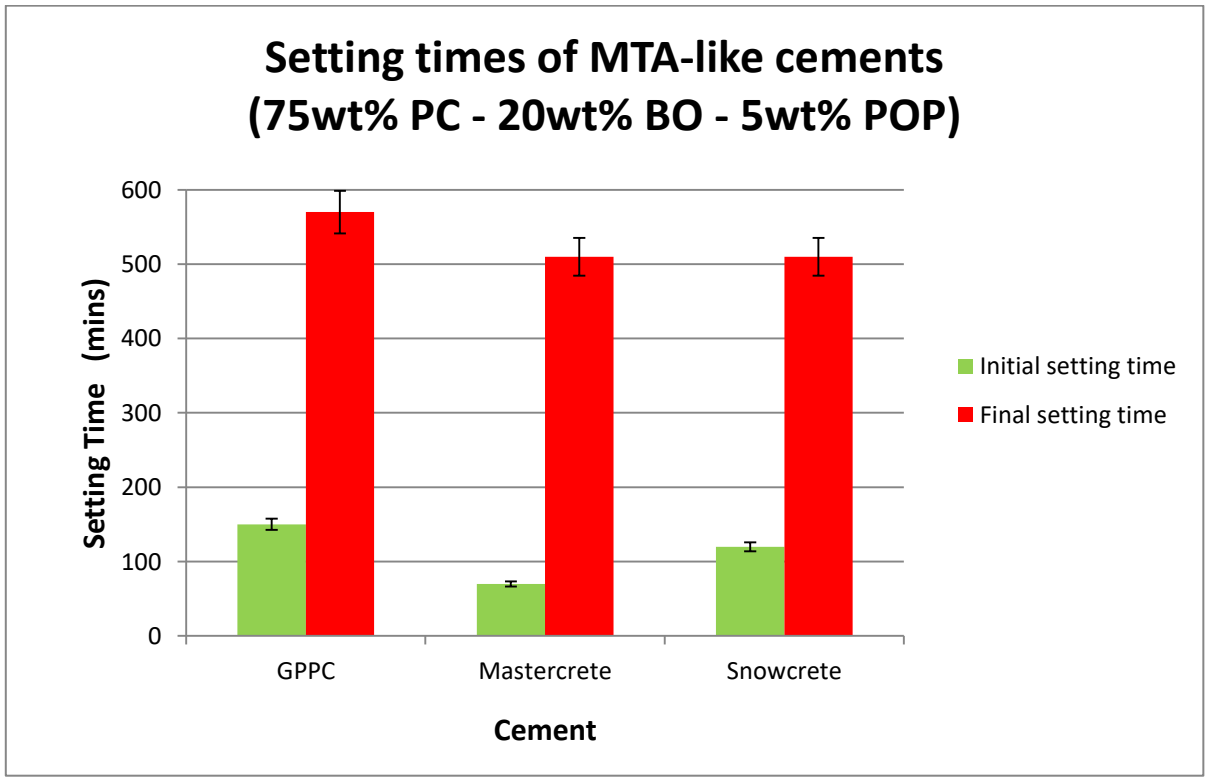

Figure 5: The setting times of all Portland cement experimental model systems (standard formulation), measured using a Gillmore needle apparatus. Both 'initial' and 'final' setting times were recorded. Constituent parts were combined to 75 wt% PC, 20 wt% Bi_2O_3 and 5 wt% POP and mixed to a PLR of 3.0 g/ml. All initial setting times were significantly different ($p < 0.05$); GPPC final setting time was significantly different to Mastercrete and Snowcrete ($p < 0.05$).

All three Portland cements were used in experimental model systems, combined to the proportions of the original grey ProRoot™ MTA (75 wt% PC, 20 wt% Bi_2O_3, 5wt% POP). Cements were then mixed at a PLR of 3.0 g/ml. Setting times are presented in Figure 5. The experimental cement containing MC reached initial and final set first (70 mins initial set; 510 mins final set), followed by the experimental system containing SC (120 mins initial; 510 mins final), then the cement mix containing GPPC (150 mins initial; 570 mins final) .

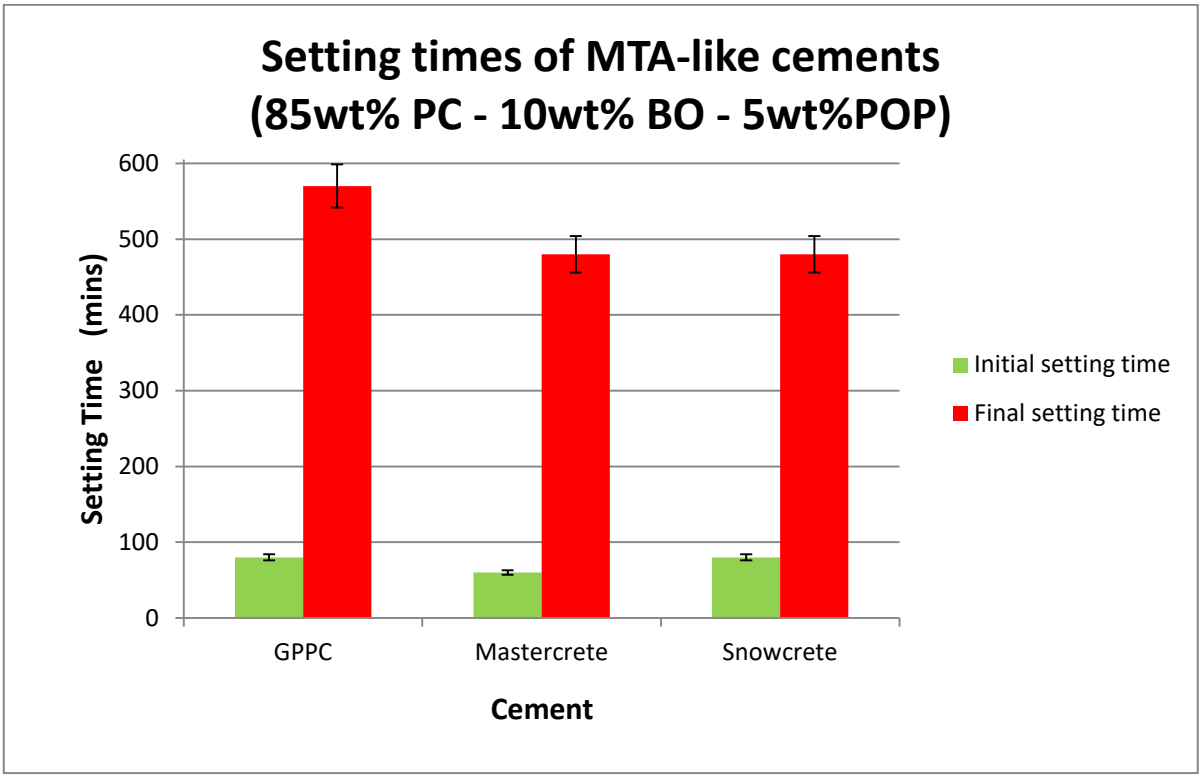

Figure 6: The setting times of all Portland cement experimental model systems (higher PC content formulation), measured using a Gillmore needle apparatus. Both 'initial' and 'final' setting times were recorded. Constituent parts were combined to 85 wt% PC, 10 wt% Bi_2O_3 and 5 wt% POP and mixed to a PLR of 3.0 g/ml. Mastercrete initial setting time was significantly different to the other cements ($p < 0.05$); GPPC final setting time was significantly different to Mastercrete and Snowcrete ($p < 0.05$).

The setting times for all Portland cements were also investigated for a higher cement-to-Bi_2O_3 ratio model system (85 wt% PC, 10 wt% Bi_2O_3, 5wt% POP). It was found that the

MC-containing experimental system set first (60 mins initial; 480 mins final), followed by the other two cement mixes (that had the same initial set, at 80 mins, though the GPPC-containing mix had a final set 90 mins later than the SC-containing cement, at 570 mins). See Figure 6.

3.1.3 Effect of POP content on setting time

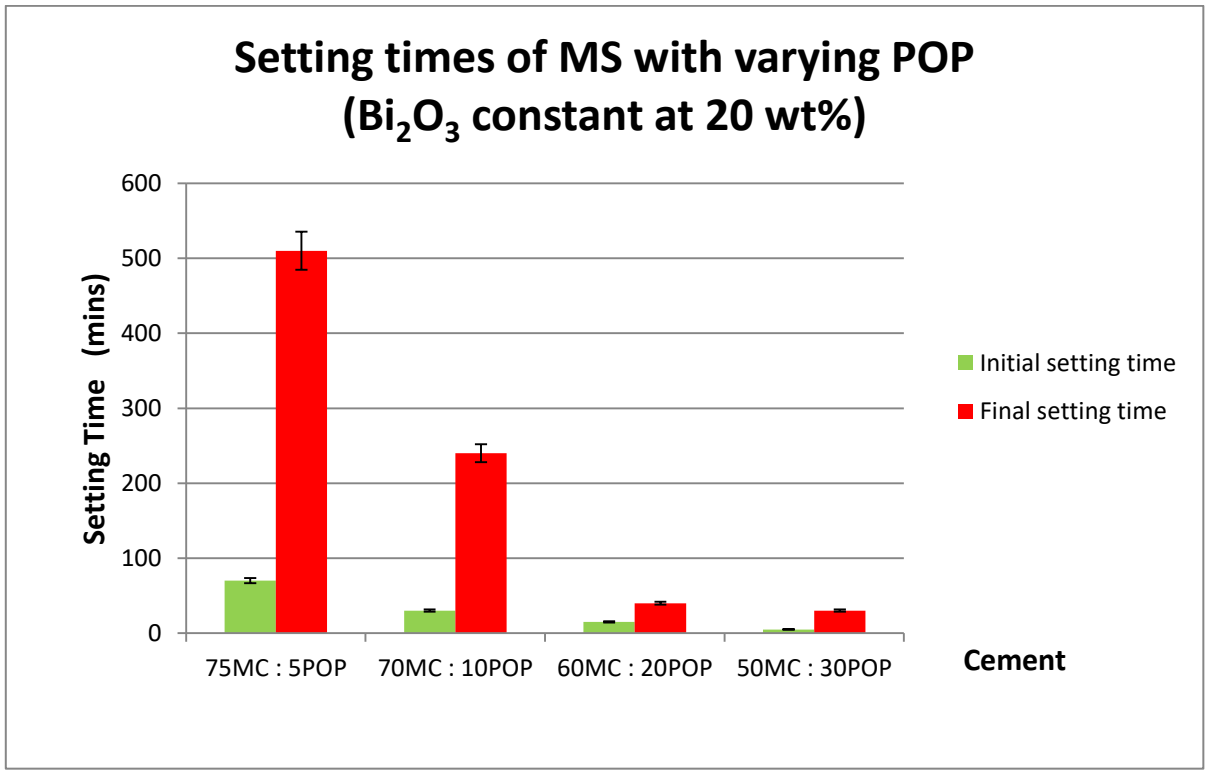

Figure 7: The setting times of MTA-like cement systems containing a set radiopacifier content (20 wt% Bi_2O_3) and variable MC-to-POP ratio (ranging from 5 – 30 wt% POP) A Gillmore needle apparatus was used for the measurements. Both 'initial' and 'final' setting times were recorded. Setting times of all cement groups significantly different ($p < 0.01$; $p < 0.05$ for difference between 20 wt% POP cement vs. 30 wt% POP cement)

After Mastercrete was chosen as the Portland cement component for the experimental model system, POP addition was then investigated using a fixed content of Bi_2O_3 (20 wt%) and a variable MC-to-POP ratio, to see the effect POP had on setting times. Of the

experimental systems tested, the cement containing the most POP (30 wt%) set the quickest (5 mins initial set; 30 mins final set). As POP content was reduced, setting times increased, reaching a peak with the 5 wt% POP cement (70 mins initial set; 510 mins final set). See Fig 7.

3.1.4 Effect of PLR on setting time

With the primary model system formulation set at 75 wt% MC, 20 wt% Bi_2O_3 and 5 wt% POP, the relationship of PLR on setting time was investigated. The cement with the highest PLR (5.0 g/ml) was the quickest setting, with initial set at 10 mins, and final set at 50 mins. As the PLR decreased, the setting time increased, reaching a peak of 720 mins for initial set, and 1,260 mins for the final set (for PLR 2.0 g/ml). See Fig 8.

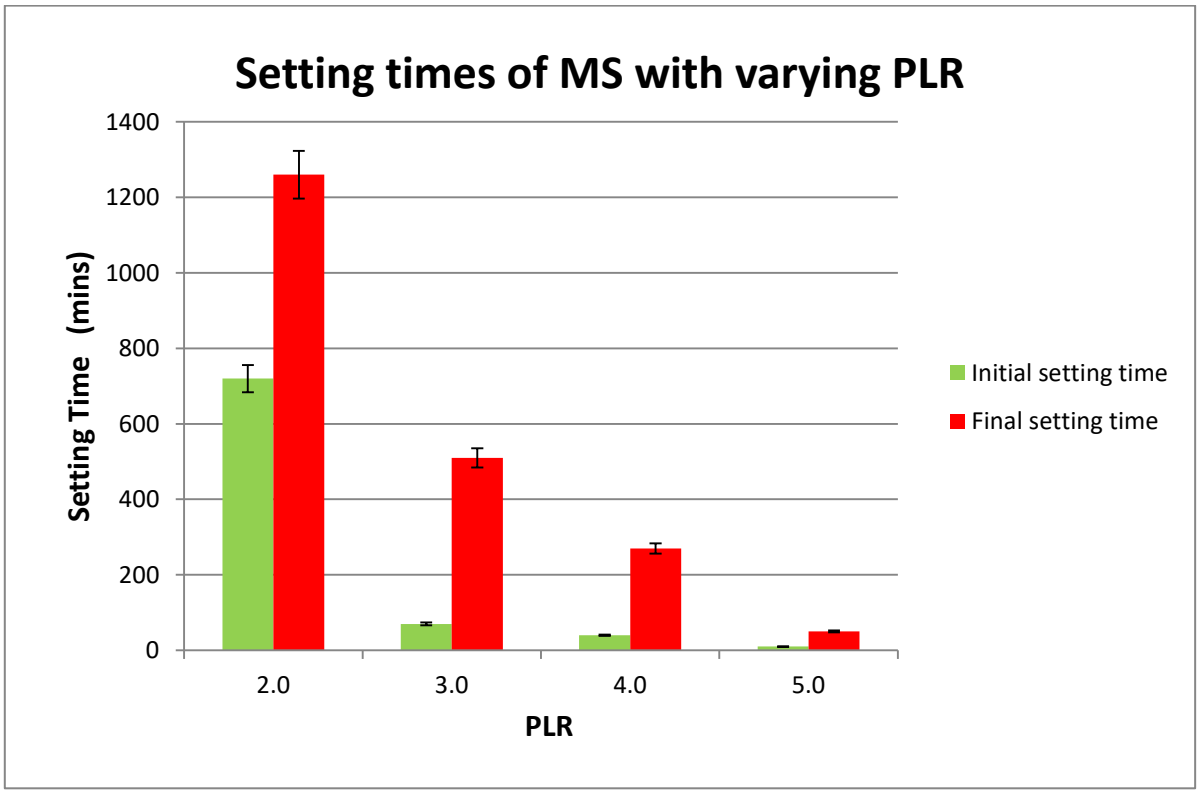

Figure 8: The setting times of the primary model system (75 wt% MC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied PLR (2.0 – 5.0 g/ml). A Gillmore needle apparatus was used for the measurements. Both 'initial' and 'final' setting times were recorded. Setting times of all cement groups significantly different ($p < 0.01$; $p < 0.05$ for difference between initial setting time of PLR 3.0 g/ml cement vs. 4.0 g/ml cement)

3.1.5 Effect of sample storage time on material properties

The identified best model system (75 wt% MC, 20 wt% Bi_2O_3, 5 wt% POP) was used to prepare samples for material property testing (as described in 2.1.1 – 2.1.3), however the storage duration of the samples prior to testing was varied (between 7, 10, 21 and 35 days) to investigate if storage duration affects the material properties. The lowest mean CS value was found to be associated with the samples stored for 7 days (40 MPa); CS increased with storage duration to peak at 21 days (61 MPa), prior to decreasing to 47 MPa (at 35 days). See Figure 9.

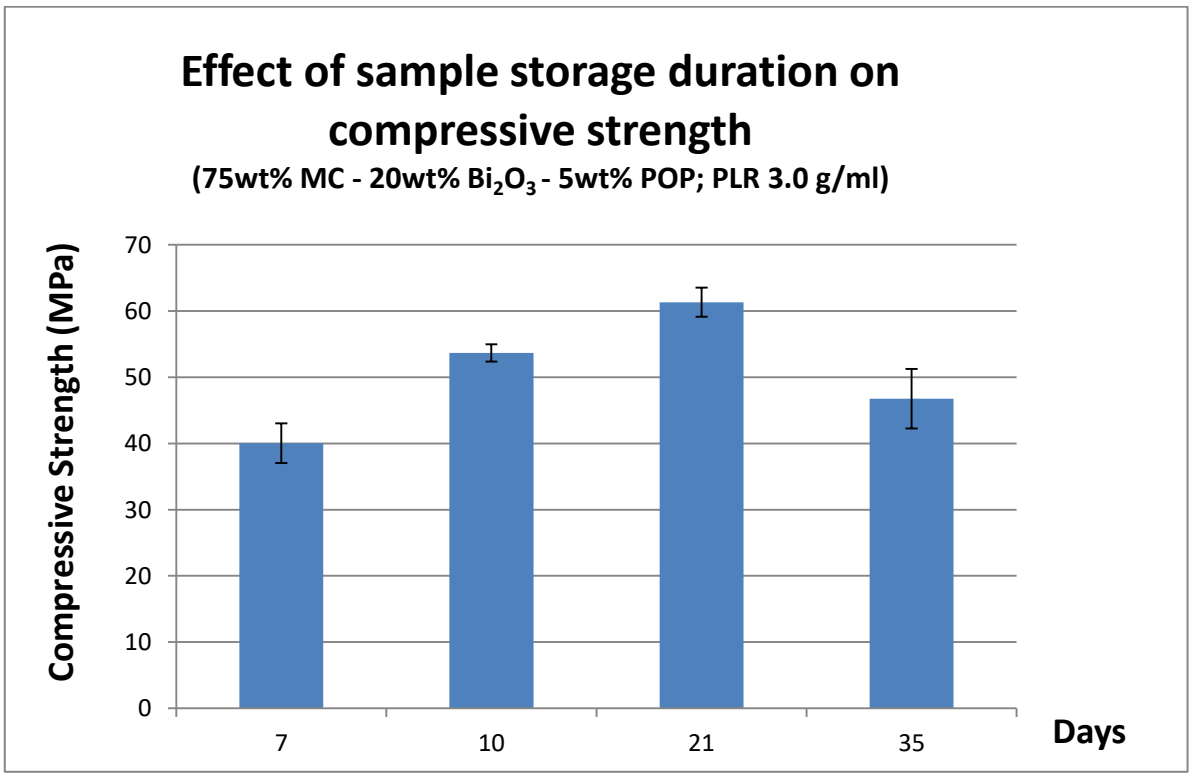

Figure 9: The compressive strength of the principal model system (75 wt% MC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied sample storage durations (7, 10, 21, 35 days). CS of all cement groups significantly different ($p < 0.05$) apart from 7-day cement vs. 35-day cement.

With regard to relative porosity, the model system samples that were stored for 7 days prior to testing were found to have the greatest relative porosity (22%); relative porosity decreased as storage duration increased, reaching its lowest porosity at 21 days storage duration (18%), prior to increasing slightly again. See Figure 10.

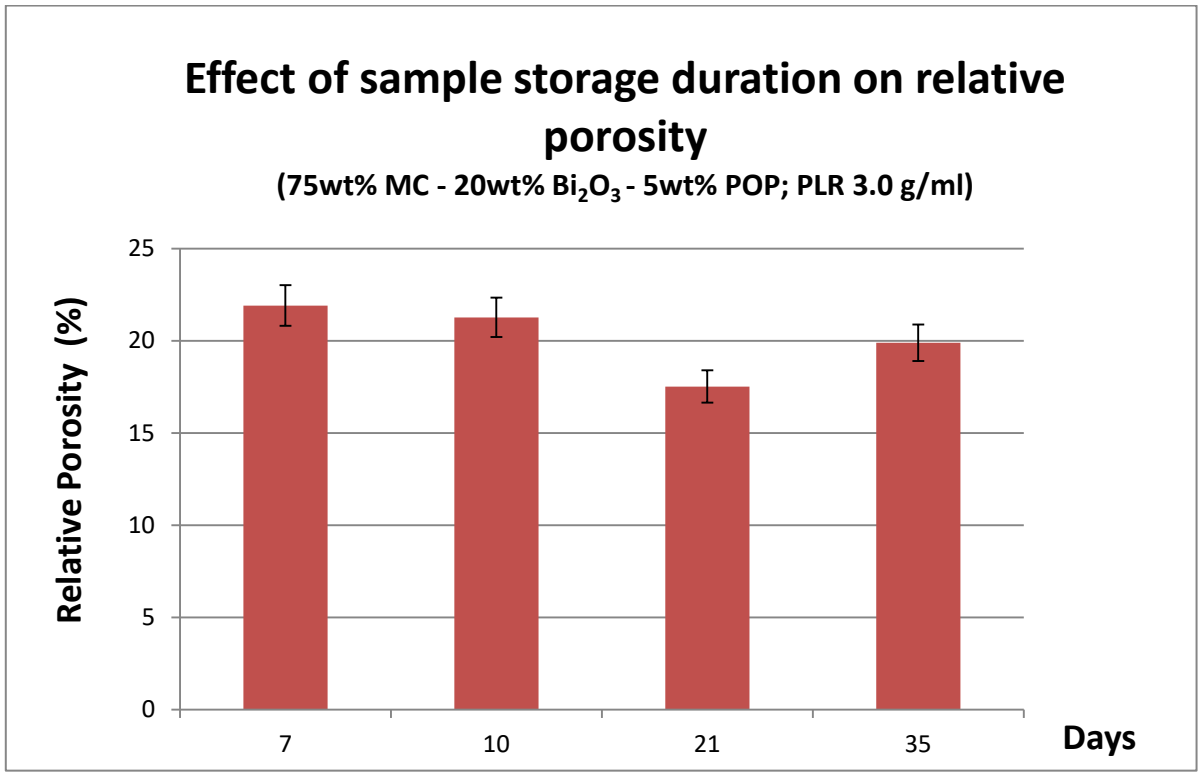

Figure 10: The relative porosity of the principal model system (75 wt% MC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied sample storage durations (7, 10, 21, 35 days). RP of 21-day cement significantly different from other cements only ($p < 0.05$).

Apparent dry density was found to be at its highest at 21 days storage (2.18 g/cm^3), with the other storage durations having very similar values to each other (2.06 – 2.08 g/cm^3). Strut density was highest for 7 days storage (2.66 g/cm^3), though the values measured for the other storage times were also very close in value (2.62 – 2.64 g/cm^3) and not statistically different. See Figure 11.

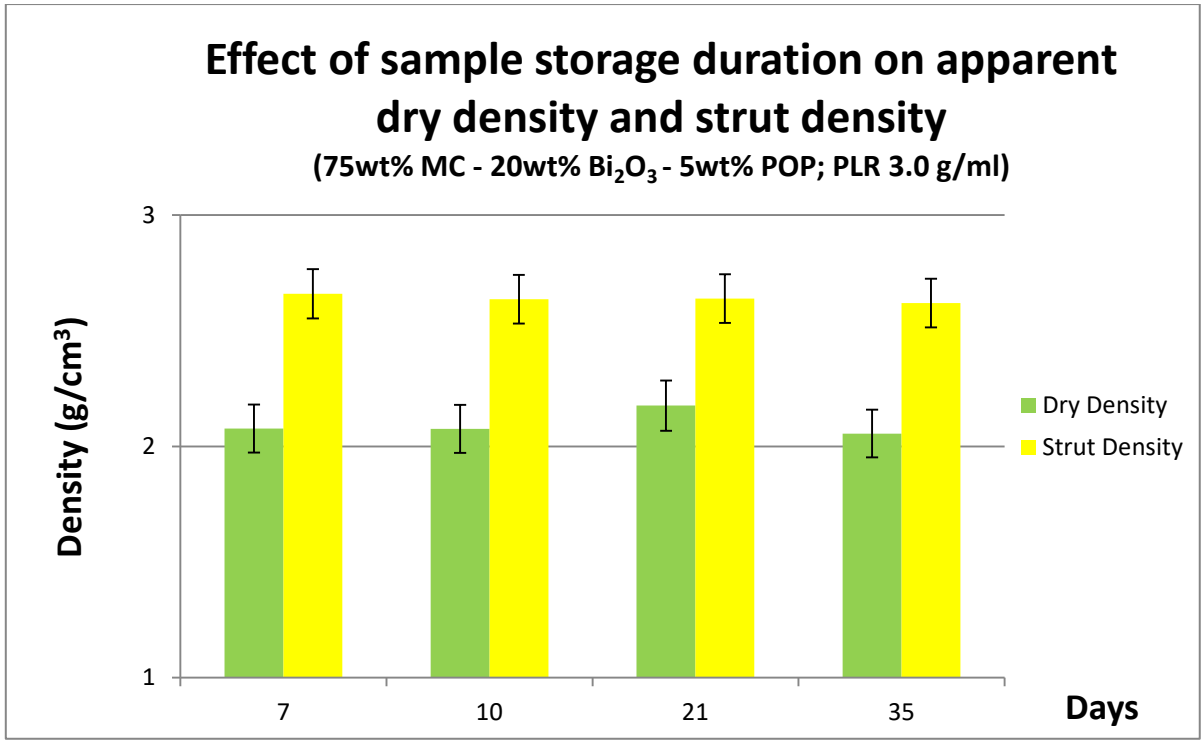

Figure 11: The apparent dry density and strut density of the principal model system (75 wt% MC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied sample storage durations (7, 10, 21, 35 days). No significant difference between cement groups.

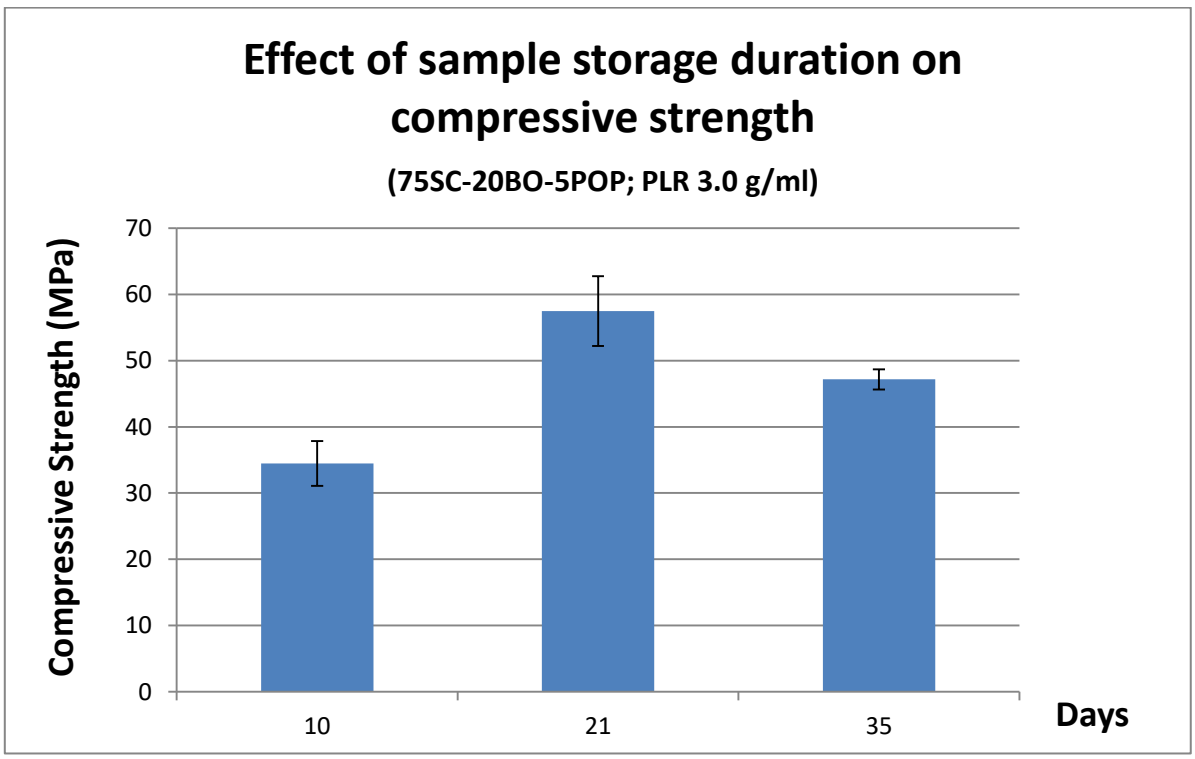

Figure 12: The compressive strength of a white MTA-like cement (75 wt% SC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied sample storage durations (10, 21, 35 days). CS of all cement groups significantly different ($p < 0.05$)

Another batch of samples were made (as described in 2.1.1 – 2.1.3) in the same constituent proportions as the model system, though Mastercrete was replaced by Snowcrete Portland cement (75 wt% SC, 20 wt% Bi_2O_3, 5 wt% POP) to create a white MTA-like cement. Storage duration days were 10, 21 and 35; the 7 day storage duration batch was excluded as it was associated with poorer material properties compared to the other three groups. See Figure 12. It was again found that the peak CS measurement was from the samples stored for 21 days prior to fracture (57 MPa); 10 days storage yielded the lowest CS measurement (34 MPa) and 35 days produced a stronger cement (47 MPa).

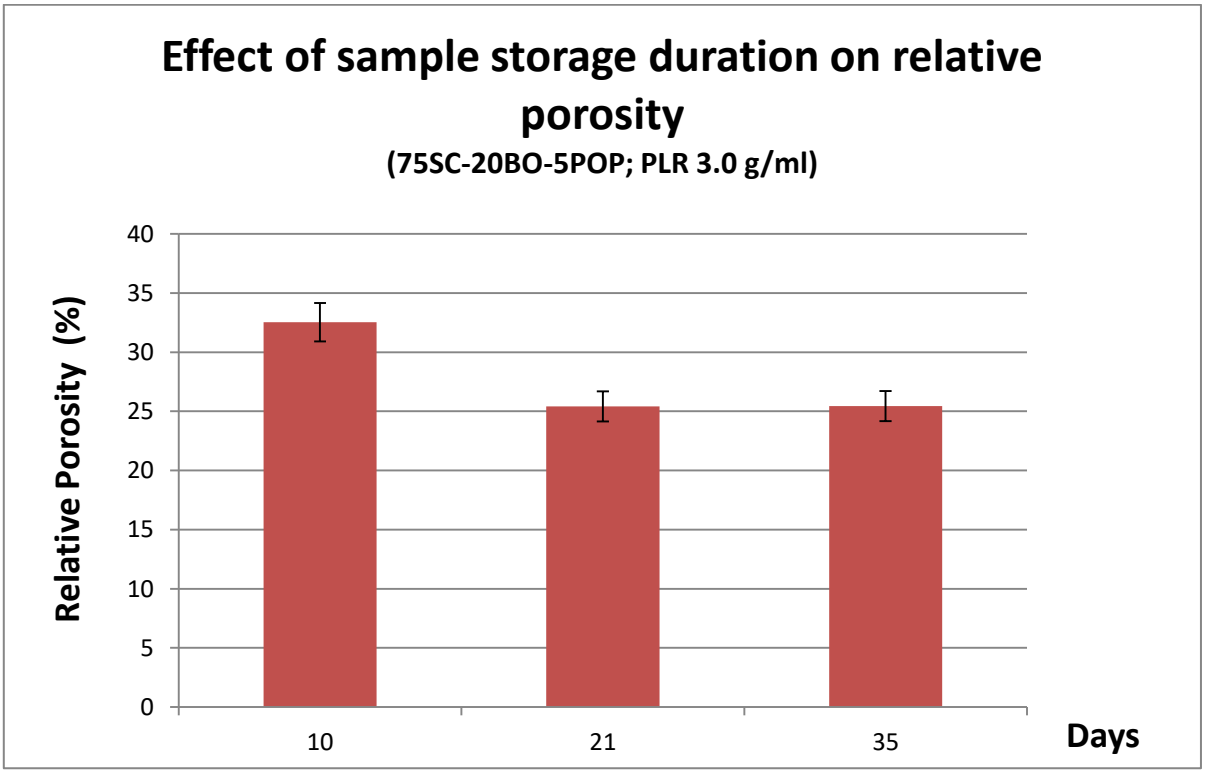

Figure 13: The relative porosity of a white MTA-like cement (75 wt% SC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied sample storage durations (10, 21, 35 days). RP of 10-day cement significantly different from other cements only ($p < 0.05$).

The relative porosity of this white MTA-like cement was the greatest at 10 days storage duration (33%). Both 21 and 35 storage days were found to produce a less porous cement, both of which had the same relative porosity (25%). See Figure 13.

The apparent dry density of this cement was highest at 21 and 35 days (1.90 g/cm^3 and 1.89 g/cm^3 respectively), though the cement stored for 10 days was similar (1.84 g/cm^3) and the difference statistically insignificant. The strut densities for all three groups were relatively close (ranging from 2.53 g/cm^3 – 2.59 g/cm^3). See Figure 14.

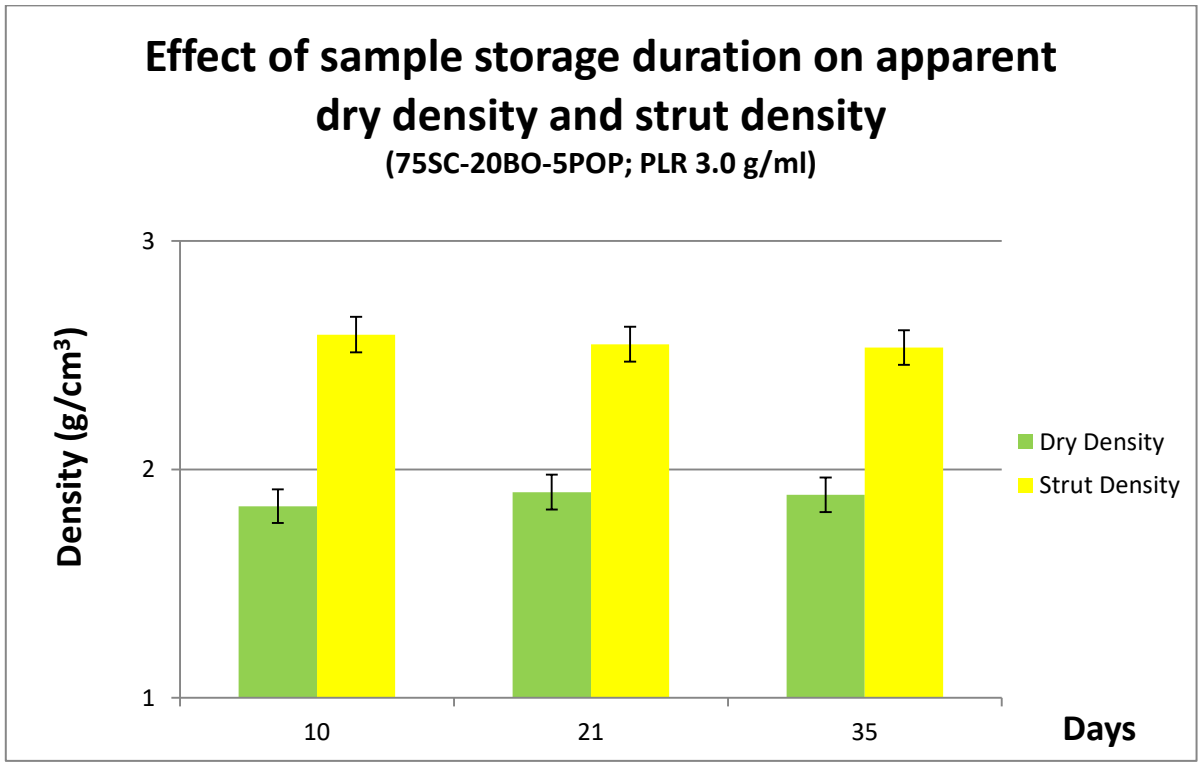

Figure 14: The apparent dry density and strut density of a white MTA-like cement (75 wt% SC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied sample storage durations (10, 21, 35 days). No significant difference between cement groups.

3.1.6 How sample storage time affects the material properties of a POP-free cement

To investigate whether a POP-free cement system was influenced differently by storage time, POP was not included in the model system, and the Bi_2O_3 content maintained at 20 wt%. Cements were stored for 10, 21, 35 and 63 days, prior to being tested. Again it was found that the peak CS measure was associated with storage of 21 days (49 MPa). 10 days yielded the weakest cement (30 MPa); 35 and 63 days storage produced cements with similar CS values of 44 MPa and 43 MPa respectively. See Figure 15.

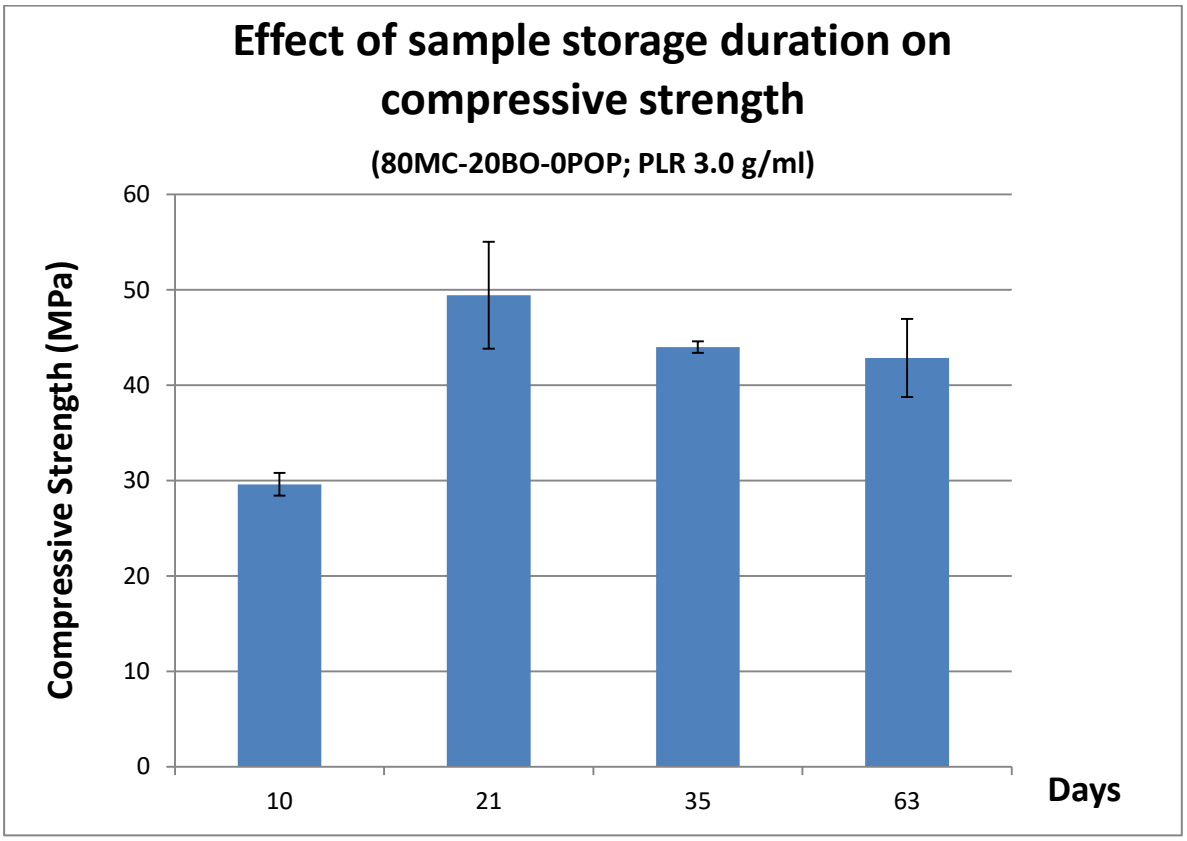

Figure 15: The compressive strength of a POP-free MTA-like cement (80 wt% MC, 20 wt% Bi_2O_3 and 0 wt% POP) with varied sample storage durations (10, 21, 35, 63 days). CS for 10-day and 21-day cements are significantly different from all cement groups ($p < 0.05$); 35-day and 63-day cement groups are not significantly different from each other.

Like the other cements tested, the samples stored for 21 days had the lowest relative porosity (16%). 35 and 63 day storage produced cements with the same relative porosity value (18%), that was not statistically different from the 21 day samples. 10 day storage yielded the poorest quality cement with the greatest relative porosity for this system. See Figure 16.

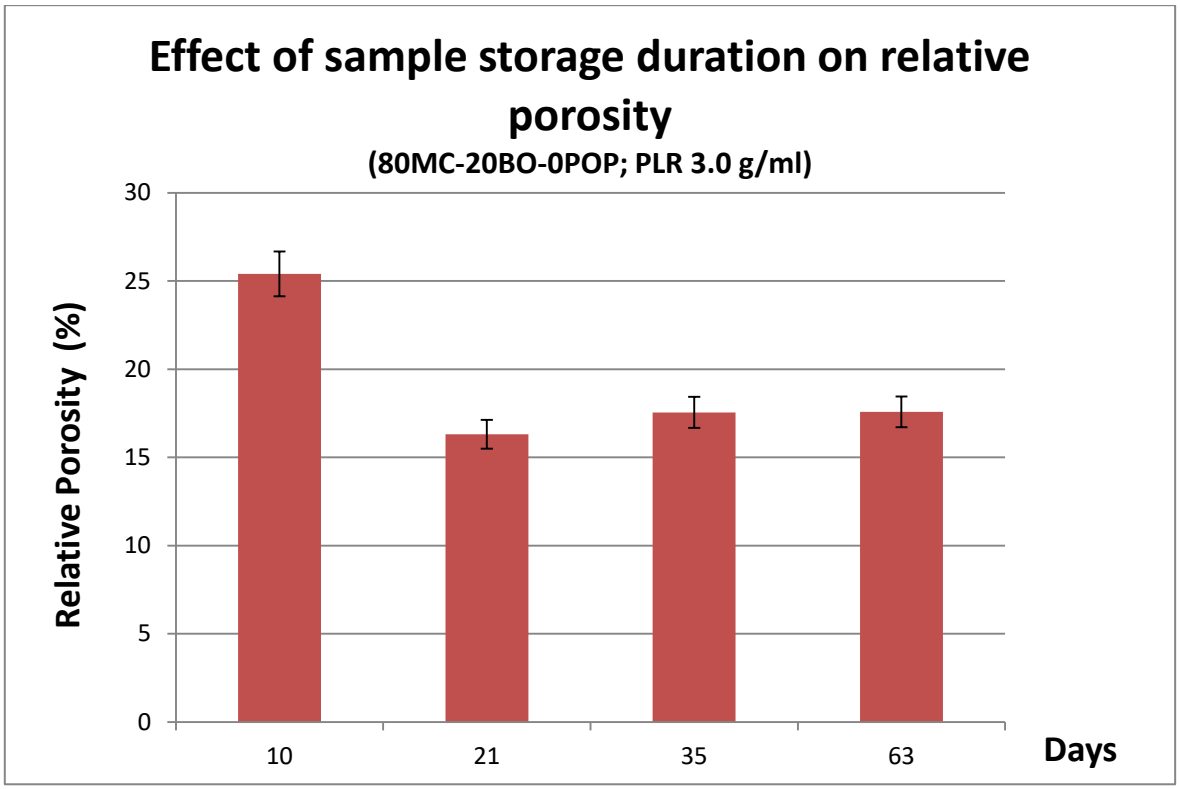

Figure 16: The relative porosity of a POP-free MTA-like cement (80 wt% MC, 20 wt% Bi_2O_3 and 0 wt% POP) with varied sample storage durations (10, 21, 35, 63 days). RP of 10-day cement significantly different from other cements only ($p < 0.01$).

Again, the apparent dry density of this material was at its lowest at the 10 day storage time (1.98 g/cm^3). The other apparent dry densities were very close in value (ranging from 2.14 g/cm^3 to 2.18 g/cm^3). All strut density measurements were relatively close to each other (ranging from 2.59 g/cm^3 to 2.65 g/cm^3) and not statistically different. See Figure 17.

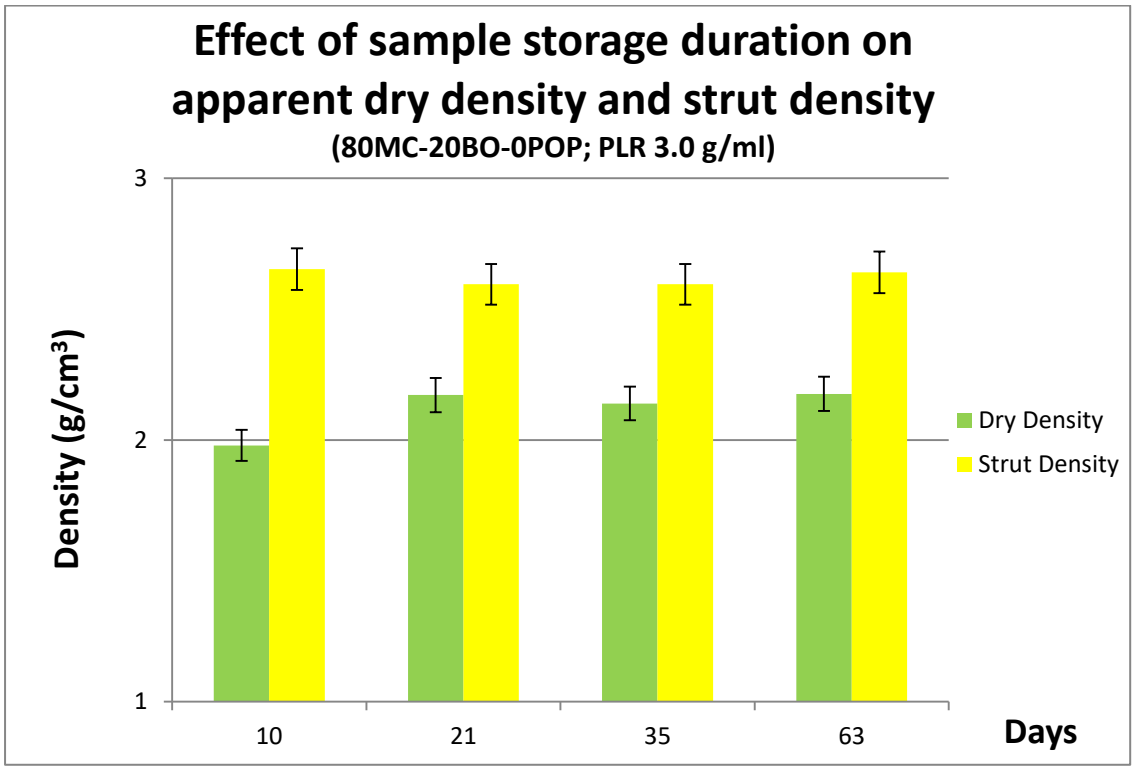

Figure 17: The apparent dry density and strut density of a POP-free MTA-like cement (80 wt% MC, 20 wt% Bi_2O_3 and 0 wt% POP) with varied sample storage durations (10, 21, 35, 63 days). No significant difference between cement groups apart from the dry density of 10-day cement compared to all other cements ($p < 0.05$)

3.1.7 POP and its effect on the material properties of an MTA-like cement

To investigate the effect of POP on the material properties of the model cement system, POP content was varied from 0 wt% - 20 wt%, with the Bi_2O_3 radiopacifier content maintained at 20 wt%. As the storage duration of 21 days had shown to provide the samples with the highest strength; this time period was chosen for this experiment.

CS was found to be at its lowest at 20 wt% POP (25 MPa), which increased in value as POP content was reduced, to a peak CS at 5 wt% POP (61 MPa). The cement with 0 wt% reduced in strength (49 MPa) from the 5 wt% POP cement, though had a higher CS value than the 10 wt% and 20 wt% systems. See Figure 18.

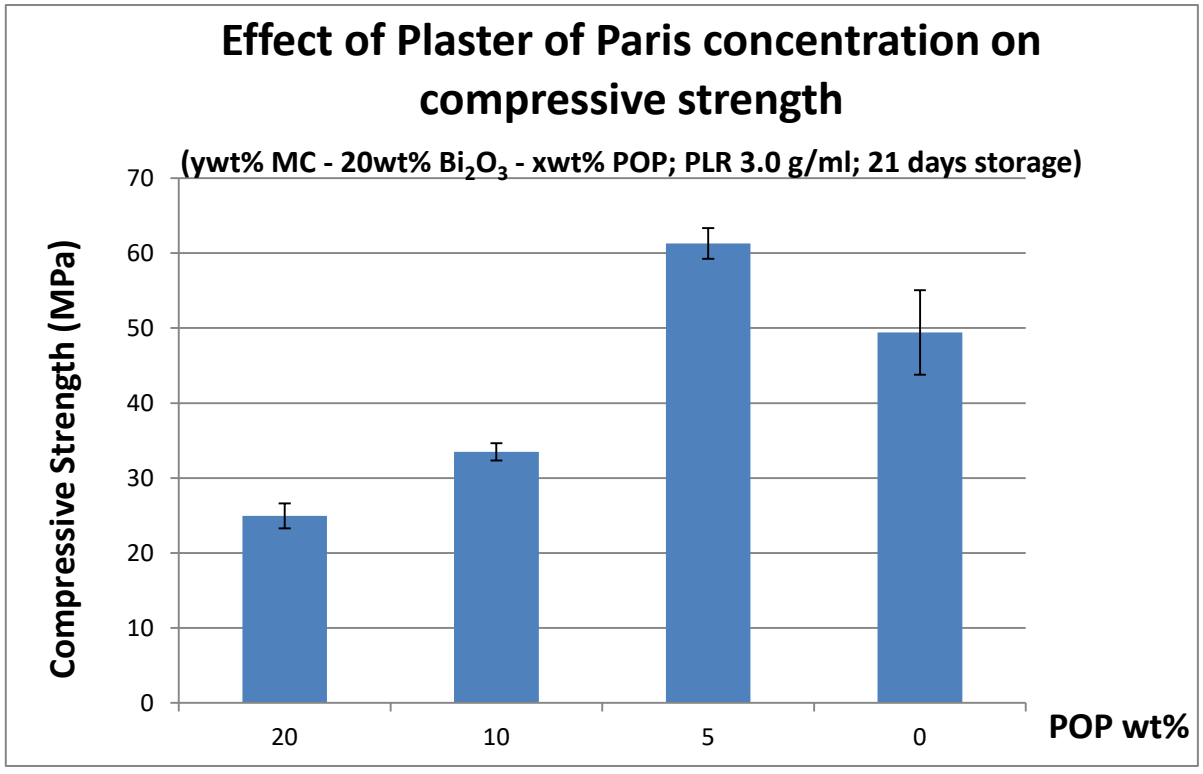

Figure 18: The compressive strength of MTA-like cements with variable POP content. Bi_2O_3 content was maintained at 20 wt%, with the content of Mastercrete Portland cement used to counter-balance the concentration of POP in the cement. CS for all cements are significantly different ($p < 0.01$); 0 wt % POP cement vs. 5 wt % POP cement and 10 wt % POP cement vs. 20 wt % POP cement have statistical significances of $p < 0.05$.

The relative porosity of the samples was highest at a POP concentration of 20 wt% (28%). See Figure 19. This progressively decreased to the lowest porosity, associated with the POP-free cement. The relative porosity of 5 wt% POP cement (16%) was very close to the 0 wt% POP system (18%), whereas the 10 wt% and 20 wt% POP cements had similar porosity values (26-28%).

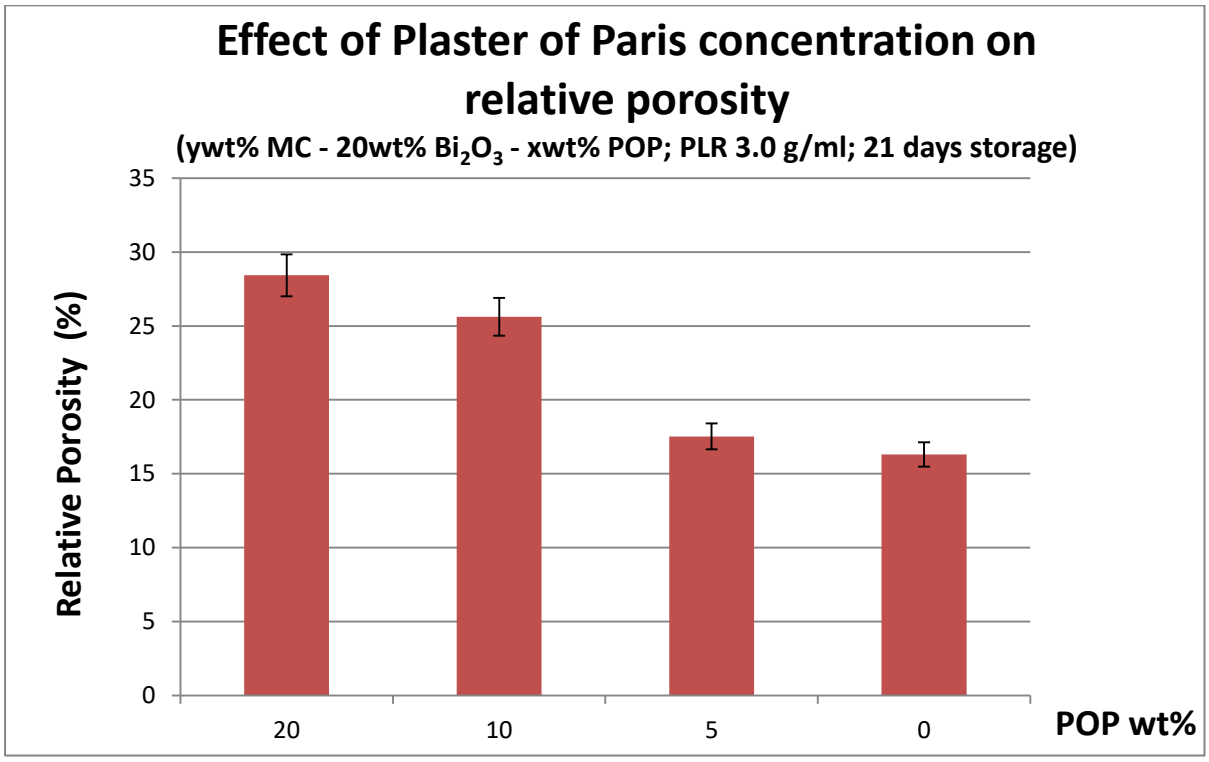

Figure 19: The relative porosity of MTA-like cements with variable POP content. Bi_2O_3 content was maintained at 20 wt%, with the content of Mastercrete Portland cement used to counter-balance the concentration of POP in the cement. RP for all cements are significantly different ($p < 0.05$) apart from 0 wt % POP cement vs. 5 wt % POP cement.

When it came to the effect of POP addition on the apparent dry density and strut density of MTA-like cements, the lowest apparent dry density was seen for the 20 wt% POP cement (1.91 g/cm^3), closely followed by the 10 wt% POP system (1.99 g/cm^3). See Figure 20. The 5 wt% and POP-free cement systems had higher and near identical dry densities (2.18 g/cm^3 and 2.17 g/cm^3 respectively). The strut densities for all samples were very similar (ranging from 2.60 – 2.67 g/cm^3)

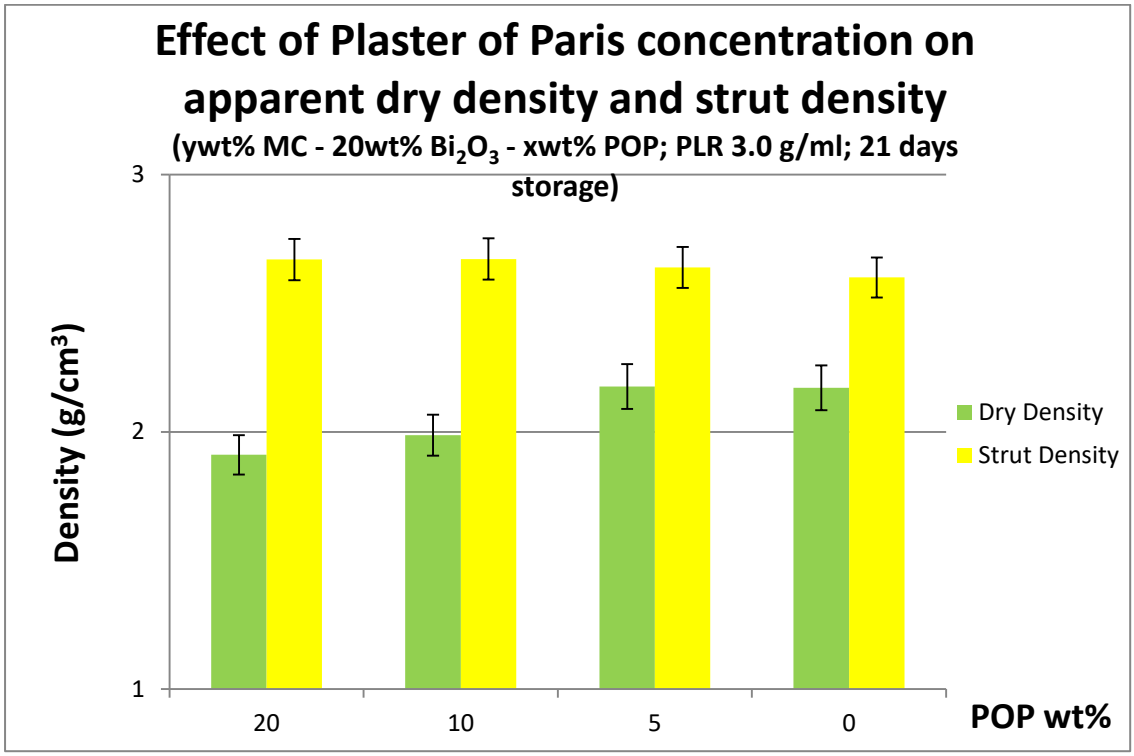

Figure 20: The apparent dry density and strut density of MTA-like cements with variable POP content. Bi_2O_3 content was maintained at 20 wt%, with the content of Mastercrete Portland cement used to counter-balance the concentration of POP in the cement. Dry densities for 0 wt% POP cement and 5 wt% POP cement significantly different ($p < 0.05$) from the other two cements; no significant difference between any other groups.

3.1.8 Effect of storage time and PLR variation on material properties

In section 3.1.5, the material properties of the primary model system (75 wt% MC, 20 wt% Bi_2O_3, 5 wt% POP) and white version (where MC is replaced by SC), mixed to the commercial MTA recommended PLR (3.0 g/ml) and stored for various durations, are presented. To investigate if a change in PLR affected these materials, the experiment in 3.1.5 was repeated with a higher PLR (4.0 g/ml). Results for both PLRs are presented alongside each other for comparison in this section.

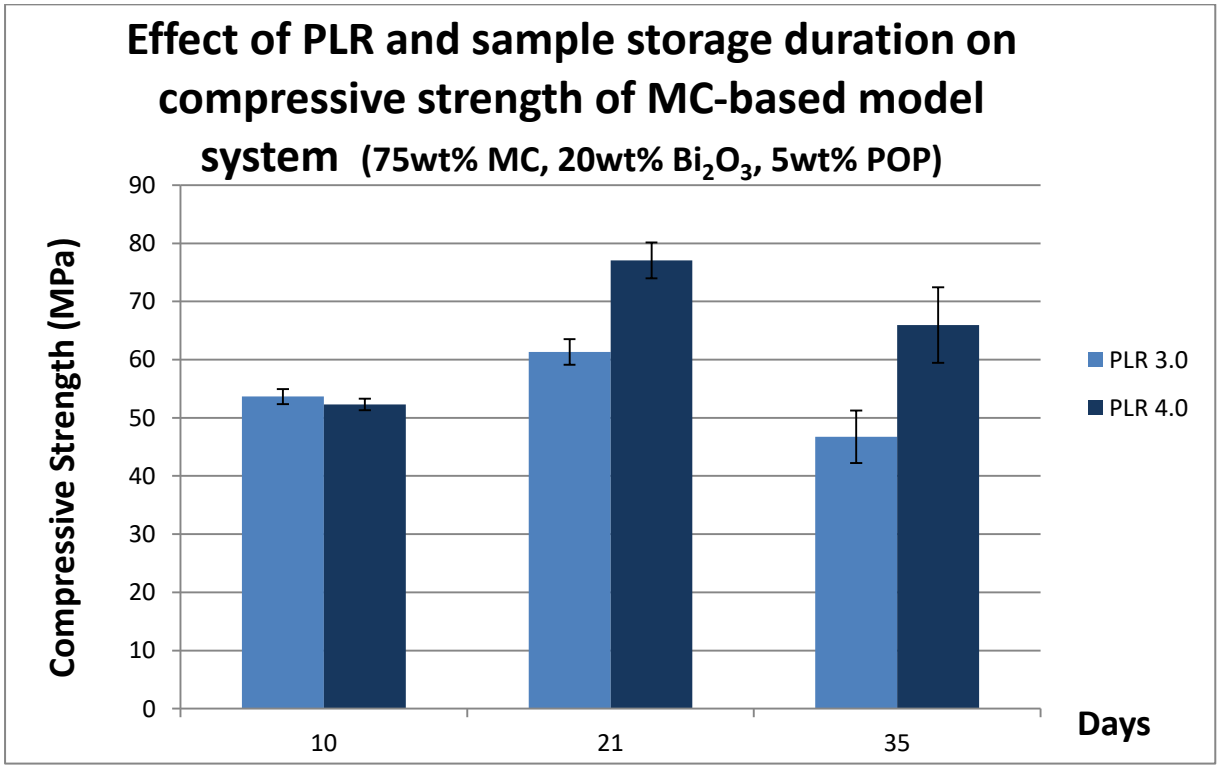

Figure 21: The compressive strength of the primary model system (75 wt% MC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied sample storage durations (10, 21, 35 days) and PLR 3.0 g/ml or 4.0 g/ml. CS significantly different ($p < 0.01$) between PLR 3.0 g/ml and 4.0 g/ml at 21 and 35 days. CS is significantly different ($p < 0.05$) between groups within each PLR.

Considering the primary model system at PLR 4.0 g/ml first, the peak compressive strength was achieved by the 21 day stored cement samples (77 MPa). The cement stored for 35 days delivered the second highest compressive strength (66 MPa), followed by the samples stored for 10 days (52 MPa). There was no statistically significance difference between the compressive strengths of the two PLRs in samples stored for 10 days, though significant differences ($p < 0.05$) were seen in the other two sample storage duration groups, with the higher PLR producing stronger samples. See Fig 21.

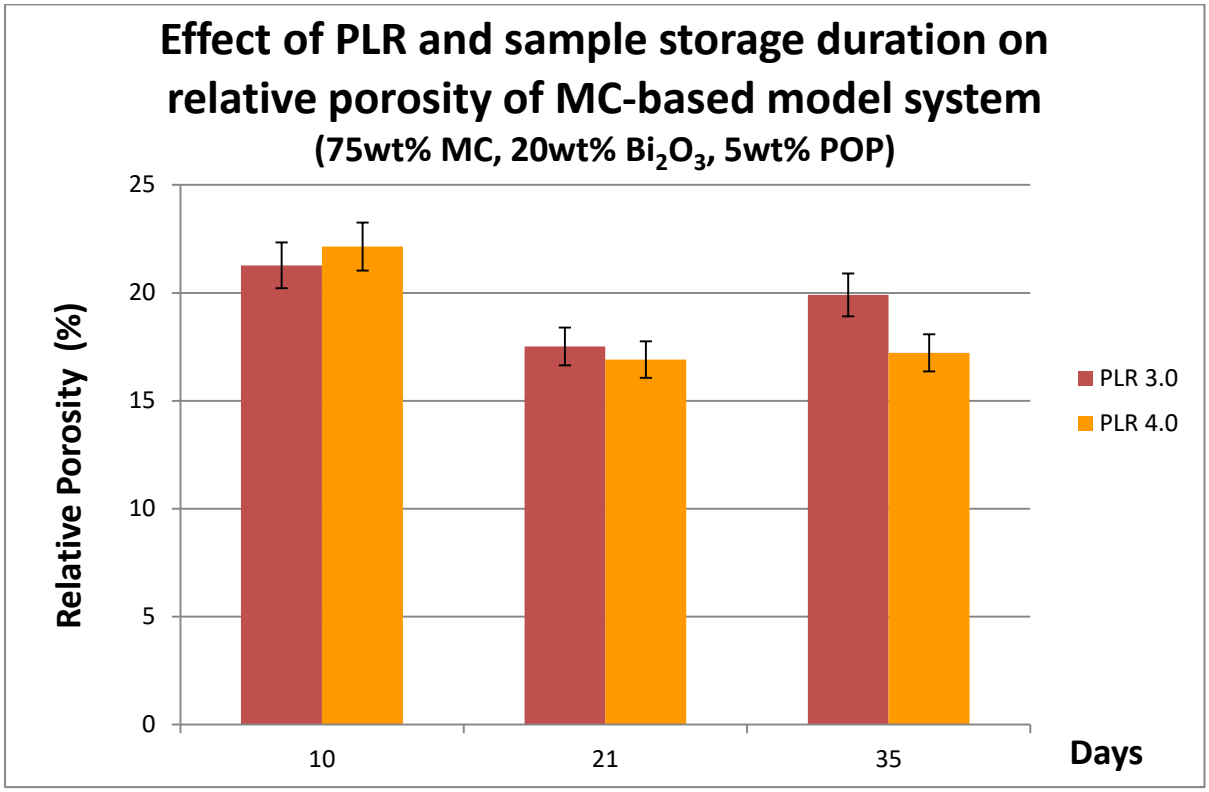

Figure 22: The relative porosity of the primary model system (75 wt% MC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied sample storage durations (10, 21, 35 days) and PLR 3.0 g/ml or 4.0 g/ml. RP significantly different ($p < 0.05$) for PLR 3.0 g/ml cements at 10 days and 35-days compared to 21-days. 21- and 35-day cements at PLR 4.0 g/ml significantly different ($p < 0.05$) to 10-day cement.

At PLR 4.0 g/ml, both the 21 day and 35 day storage durations produced the cements with the lowest relative porosity (17%); the highest relative porosity was associated with the 10 day old cement. At 10 and 21 days storage, the cements of both PLRs only had a 1% difference, which was not statistically significant. At 35 days storage, the PLR 4.0 samples had a lower mean density (17%) than those of the PLR 3.0 group (20%), which was statistically significant ($p < 0.05$). See Figure 22.

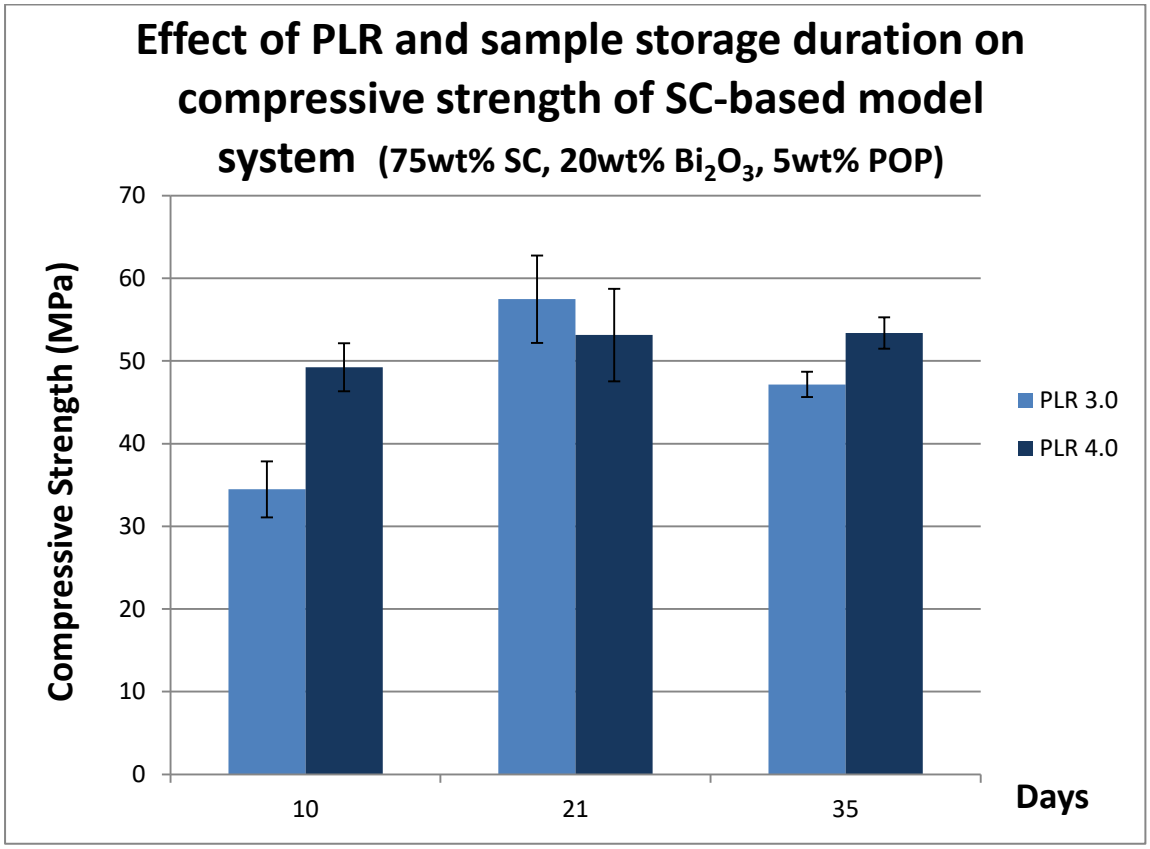

Figure 23: The compressive strength of the primary model system with Snowcrete modification (75 wt% SC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied sample storage durations (10, 21, 35 days) and PLR 3.0 g/ml or 4.0 g/ml. CS for PLR 3.0 g/ml groups significantly different ($p < 0.05$). CS between PLR cement groups at 10- and 35-day storage times were significantly different ($p < 0.05$).

Looking at the Snowcrete variation of the primary model system at PLR 4.0 g/ml, the lowest compressive strength was also found to be associated with the 10 day storage duration

(49 MPa). At 21 and 35 days storage duration, compressive strength increased and was found to be the same value for both storage times (53 MPa). Compressive strengths were lower for PLR 3.0 g/ml than 4.0 g/ml at 10 and 35 days, though the opposite was evident at 21 days (however the difference between the PLRs for that duration was not statistically significant). See Figure 23.

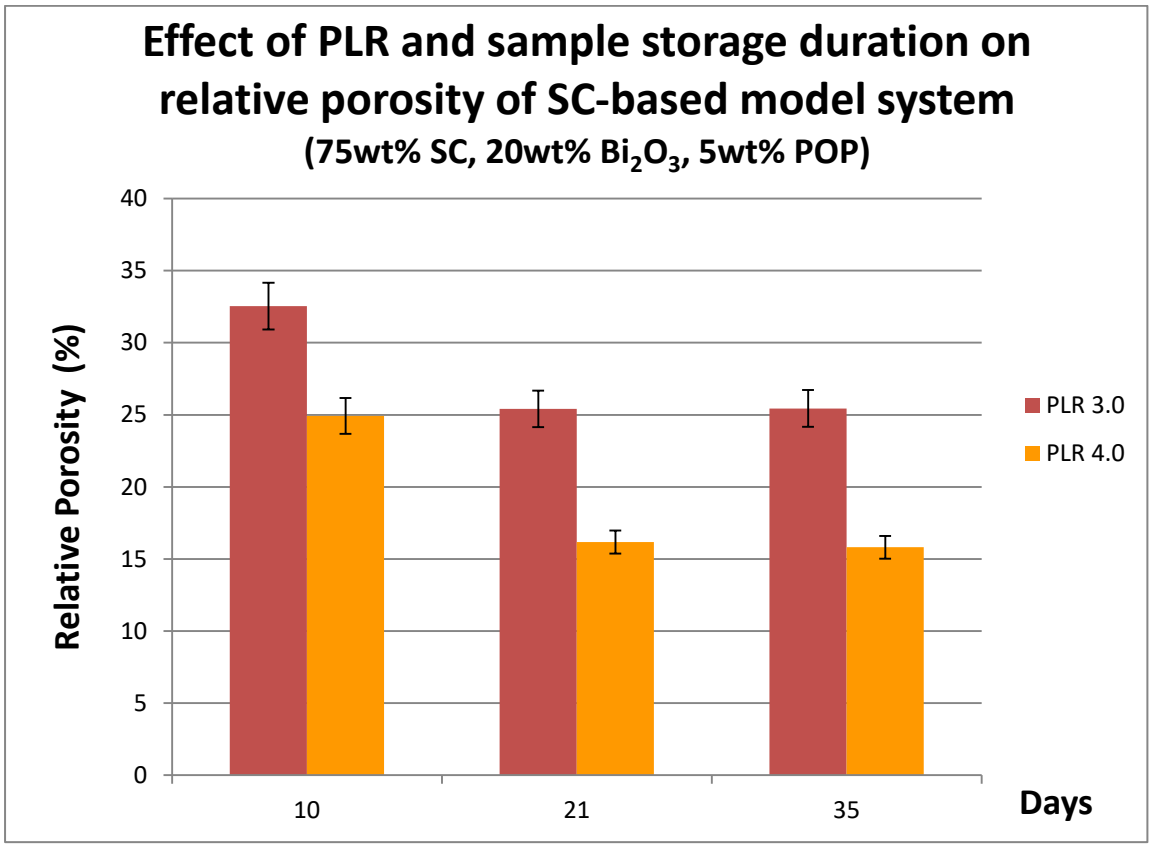

Figure 24: The relative porosity of the primary model system with Snowcrete modification (75 wt% SC, 20 wt% Bi_2O_3 and 5 wt% POP) with varied sample storage durations (10, 21, 35 days) and PLR 3.0 g/ml or 4.0 g/ml. Within PLR ratios, RP was significantly different ($p < 0.05$) between the 10-day cement and the other two mixes. When comparing between PLR groups, cements were significantly different ($p < 0.01$) at each storage duration tested.

With the PLR 4.0 g/ml group, relative porosity was found to be the highest at 10 days storage duration (25%). At 21 and 35 days storage, relative porosity decreased and was found to be the same for both groups (16%). Relative porosity was found to be lower at PLR 4.0

g/ml (than 3.0 g/ml) in all storage time groups; the differences between these mean values were all statistically significant ($p < 0.05$). See Figure 24.

3.2 The use of alternate radiopacifiers in an MTA-like model system

3.2.1 Bismuth oxide addition and the radiopacity of MTA-like cements

The model system had its lowest radiopacity when no Bi_2O_3 was added (0.83 mmAl). At 0 wt% and also 10 wt% (2.40 mmAl), the cement radiopacities fell below the ISO standard requirement of 3 mmAl. Only at 20 wt% did the cement meet the minimum required radiopacity, with 3.71 mmAl. The MTA control, grey ProRoot™ by Dentsply, had a radiopacity of 3.66 mmAl. See Figure 25.

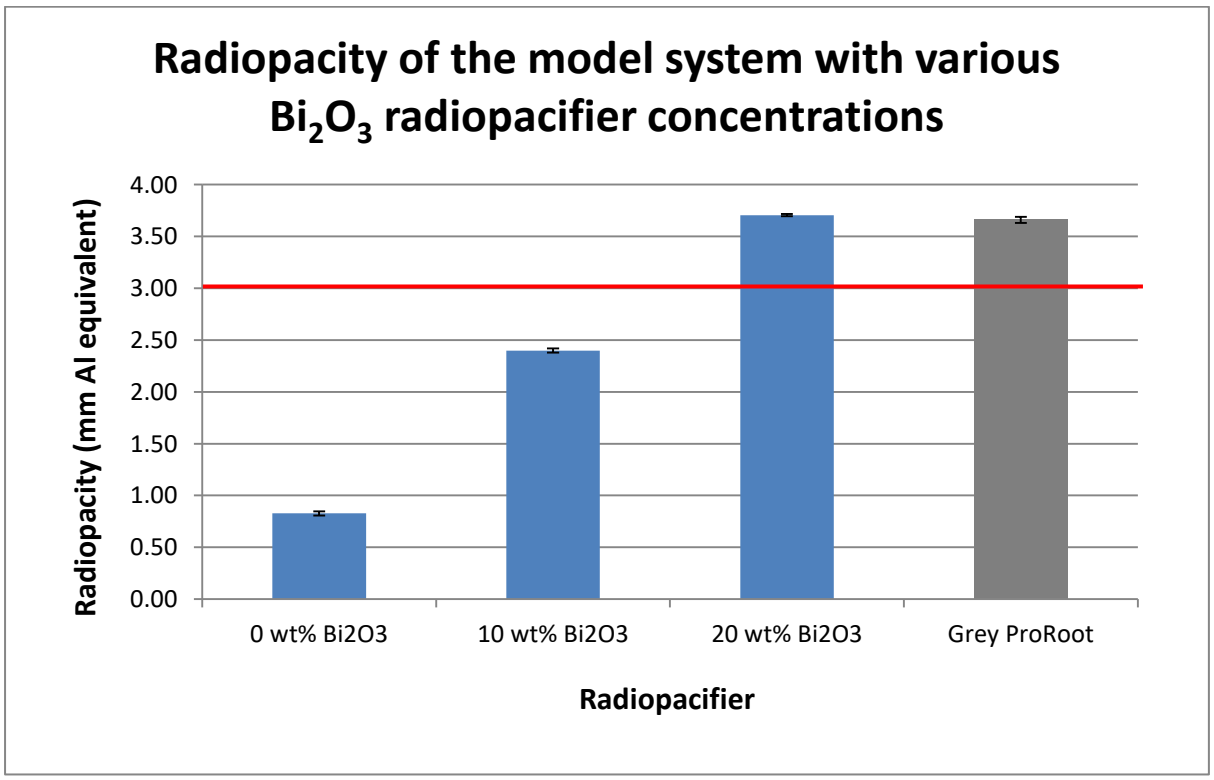

Figure 25: The radiopacity of the model system with various concentrations of Bi_2O_3 content; grey ProRoot™ MTA was used as a control. Only the cement with the 20 wt% Bi_2O_3 addition and control met the minimum ISO standard requirement of 3mm Al (red line). All groups were significantly different ($p < 0.01$) from each other, apart from the control and 20 wt% Bi_2O_3 cements.

3.2.2 Barium sulphate addition and the radiopacity of MTA-like cements

At 10 wt%, radiopacity for the $BaSO_4$-containing cement was 1.10 mmAl and at 20 wt% it was 1.48 mmAl, all of which fell below the ISO standard requirement of 3 mmAl. See Figure 26.

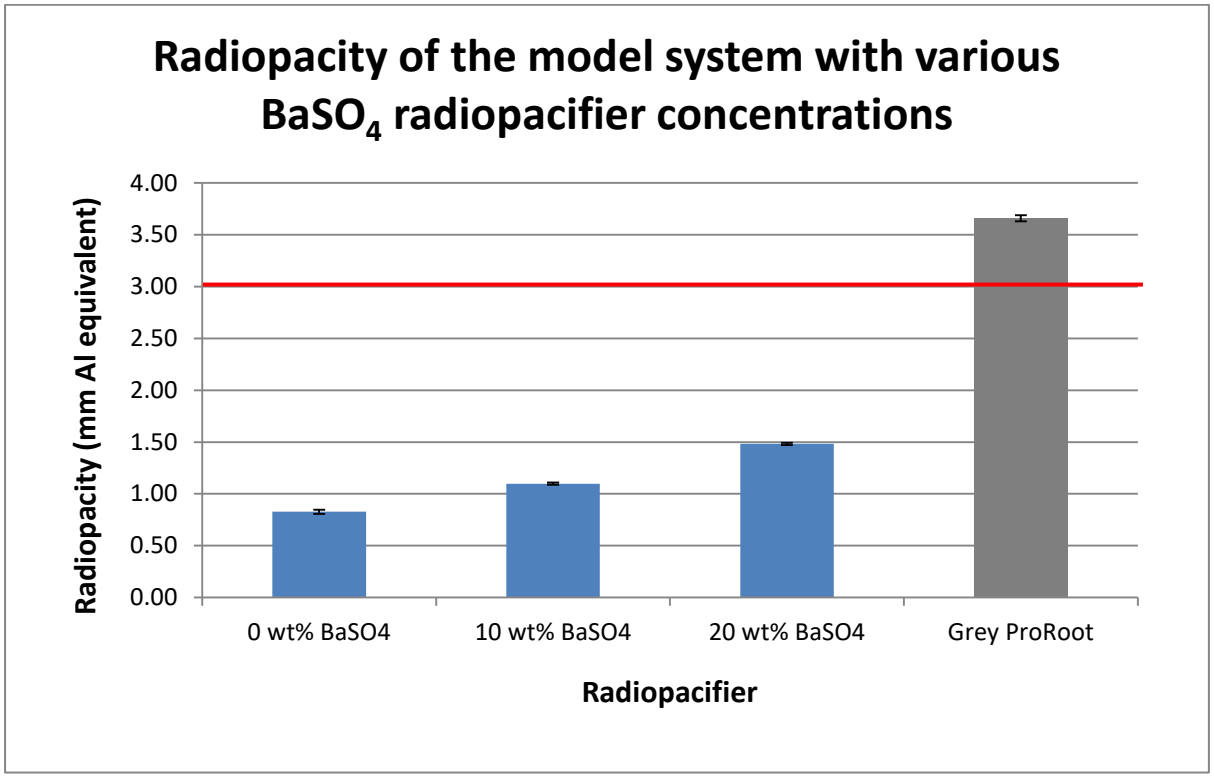

Figure 26: The radiopacity of the model system with various concentrations of $BaSO_4$ content; grey ProRoot™ MTA was used as a control. None of the model system cements met the minimum ISO standard requirement of 3mm Al (red line), though the control however did. All $BaSO_4$ groups were significantly different ($p < 0.05$) from each other; the control was significantly different ($p < 0.01$) from all $BaSO_4$ groups.

3.2.3 Tantalum pentoxide addition and the radiopacity of MTA-like cements

Ta_2O_5 addition as a radiopacifier to the model system incrementally increased radiopacity from 0.83 mmAl (at 0 wt%), to 1.73 mmAl (at 10 wt%) and 2.78 mmAl (at 20 wt%). Although the 20% addition of the radiopacifier came close to the ISO standard requirement of 3 mmAl, all versions of the model system had a lower than required level of radiopacity. See Figure 27.

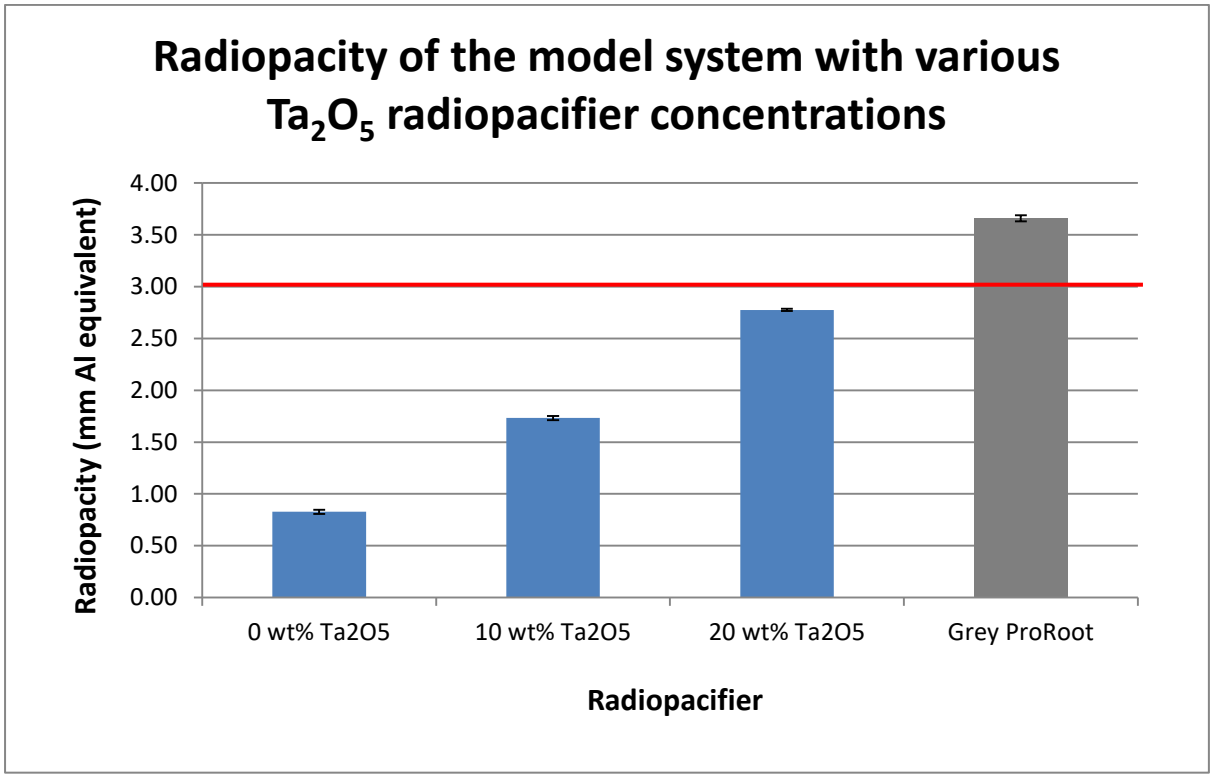

Figure 27: The radiopacity of the model system with various concentrations of Ta_2O_5 content; grey ProRoot™ MTA was used as a control. Apart from the control, none of the model system cements met the minimum ISO standard requirement of 3mm Al (red line), though 20 wt% Ta_2O_5 came close. All groups are significantly different from each other ($p < 0.05$).

3.2.4 Lanthanum oxide addition and the radiopacity of MTA-like cements

The addition of La_2O_3 increased radiopacity from 0.83 mmAl (at 0 w%), to 1.30 mmAl (at 10 wt%) and 1.85 mmAl (at 20 wt%). All samples of the model system were noticeably below the ISO standard requirement. See Figure 28.

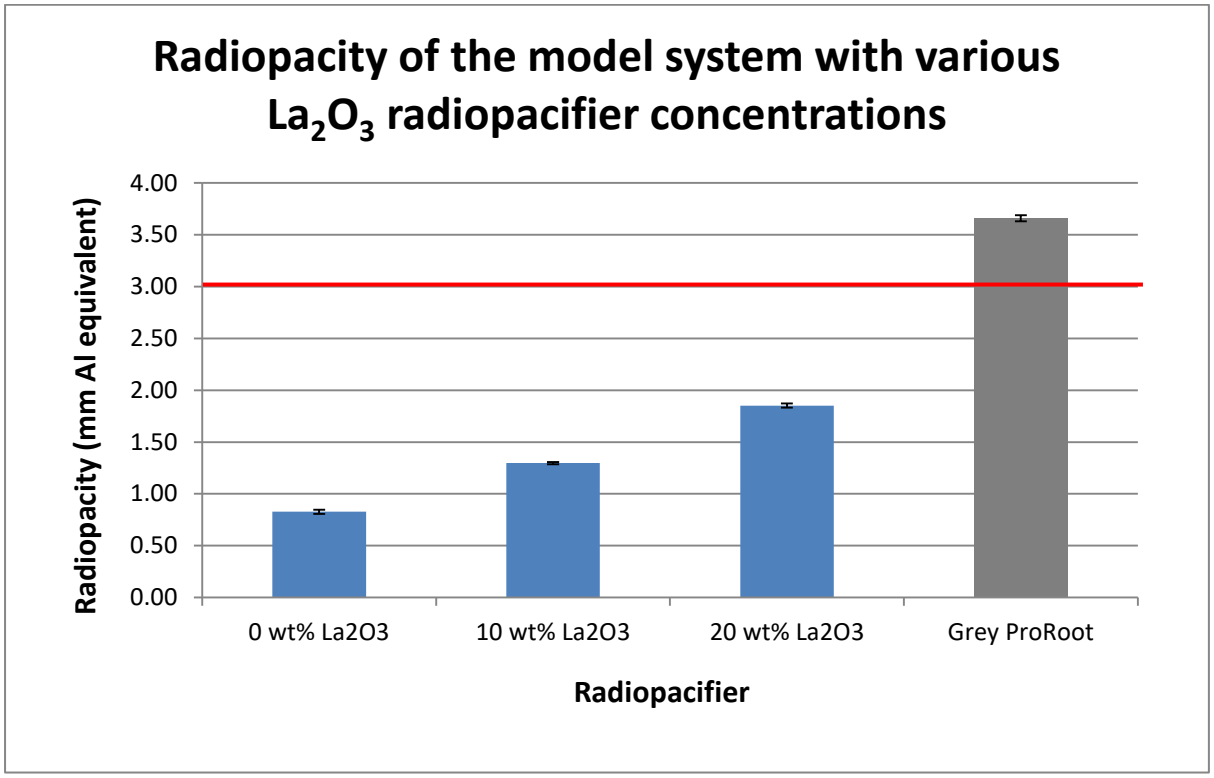

Figure 28: The radiopacity of the model system with various concentrations of La_2O_3 content; grey ProRoot™ MTA was used as a control. Although the control met the minimum ISO standard requirement of 3mm Al (red line), all the model system cements did not. All La_2O_3 groups were significantly different ($p < 0.05$) from each other; the control was significantly different ($p < 0.01$) from all La_2O_3 groups.

3.2.5 The effect of radiopacifiers on material properties of an MTA-like cement at 10 wt%

The compressive strength of the radiopacifier-free model system decreased from 68MPa to 46MPa with the 10% addition of both Bi_2O_3, and Ta_2O_5, shown in Fig 29. When La_2O_3 was added, compressive strength decreased to 32 MPa; very close to the 30 MPa achieved by the $BaSO_4$–containing model system. The control, grey ProRoot™ MTA, had a compressive strength of 34MPa, though it should be noted that its radiopacifier content was 20 wt% Bi_2O_3.

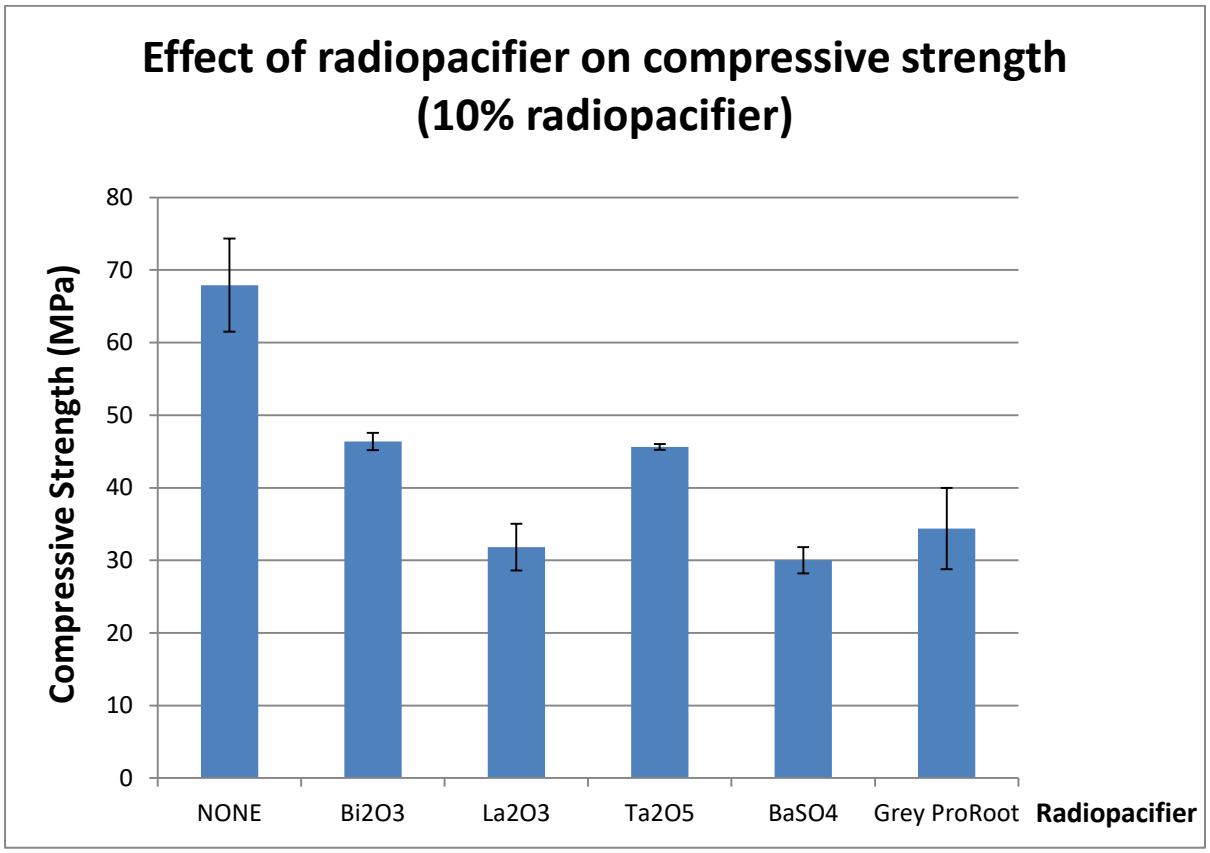

Figure 29: The compressive strength of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at 10 wt%; the model system with no radiopacifier and grey ProRoot™ MTA were used as controls. In comparison with the other groups, the CS of Bi_2O_3 and Ta_2O_5 cements were significantly different ($p < 0.05$), along with the no radiopacifier cement ($p < 0.01$).

In the 10% radiopacifier addition group, relative porosity increased from 16% to 20% with radiopacifier addition in the Bi_2O_3 and Ta_2O_5 samples. The use of La_2O_3 as a radiopacifier increased relative porosity to 21% and $BaSO_4$ to 25%. See Figure 30. The grey ProRoot™ control had the highest relative porosity (27%), though had the higher fixed content of radiopacifier (20 wt% Bi_2O_3).

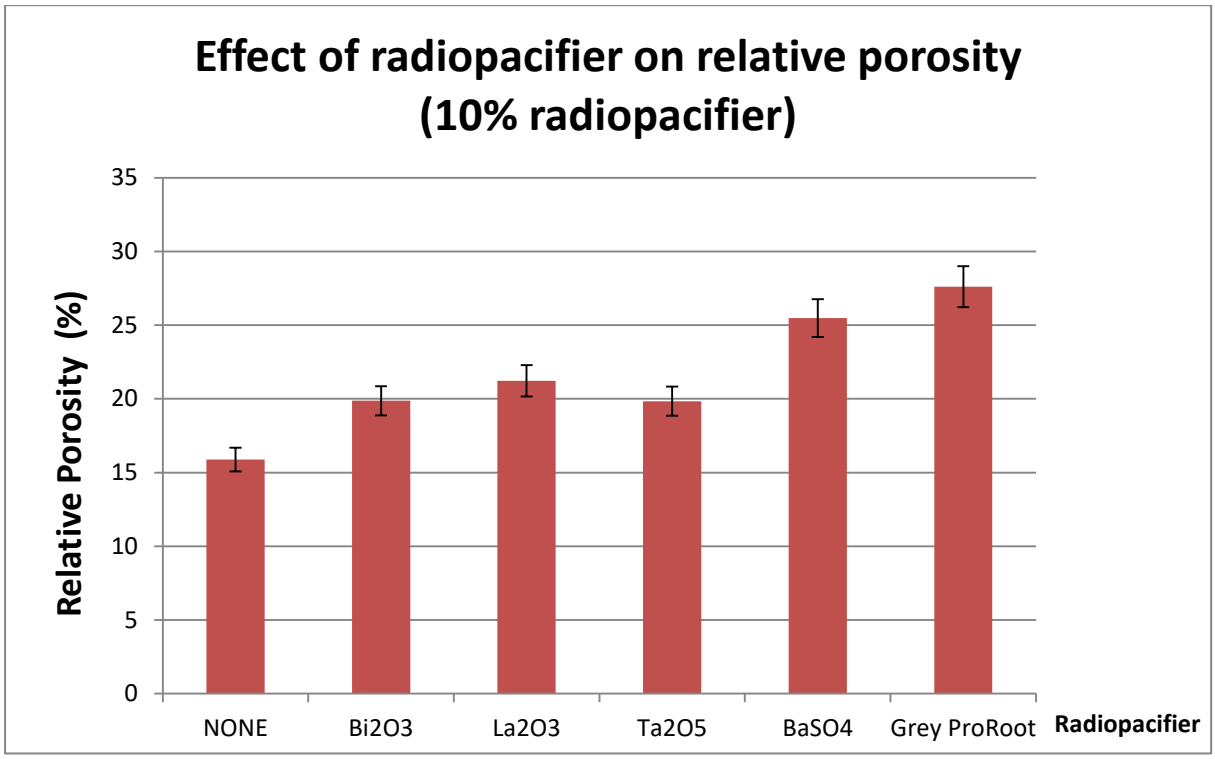

Figure 30: The relative porosity of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at 10 wt%; the model system with no radiopacifier and grey ProRoot™ MTA were used as controls. RP of Bi_2O_3, La_2O_3, Ta_2O_5 are significantly different ($p < 0.05$) to the other cements tested.

Strut density of the model system with 0 wt% radiopacifier was 2.33 g/cm^3. This increased with the addition of all radiopacifiers, especially the denser Bi_2O_3 and Ta_2O_5 compounds (2.46 g/cm^3 and 2.45 g/cm^3 respectively). The La_2O_3- and $BaSO_4$-containing cements had lower strut densities (2.44 g/cm^3 and 2.42 g/cm^3 respectively). The grey ProRoot™ control had the highest strut density (2.62 g/cm^3), though also had the fixed higher 20 wt% Bi_2O_3 content.

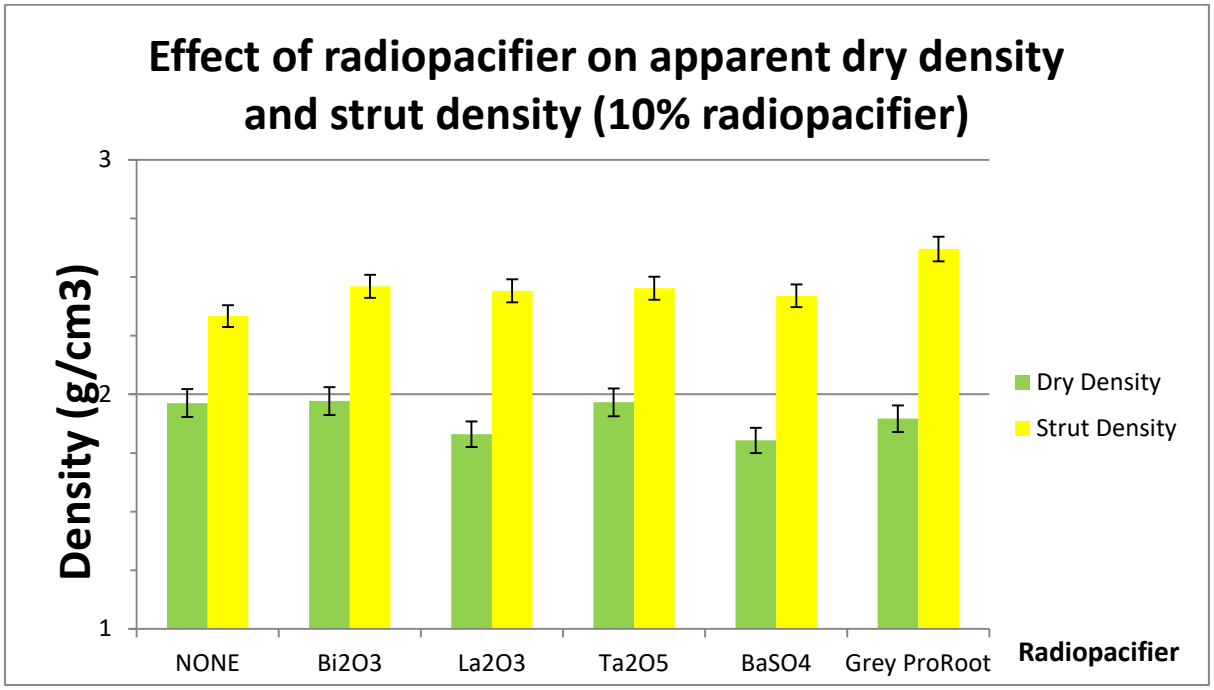

Figure 31: The apparent dry densities and strut densities of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at 10 wt%; the model system with no radiopacifier and grey ProRoot™ MTA were used as controls. The strut densities of the two controls were significantly different from those of the other cements tested ($p < 0.05$).

The apparent dry densities of the cements were lower than the strut densities, with the Bi_2O_3- and Ta_2O_5-containing cements having the highest values (both 1.97 g/cm^3), closely followed by the 0 wt% radiopacifier model system (1.96 g/cm^3). The model systems containing La_2O_3 and $BaSO_4$ were less dense again (1.83 g/cm^3 and 1.80 g/cm^3 respectively).

The commercial MTA control had an apparent dry density of 1.90 g/cm^3 (with radiopacifier content at 20%). See Figure 31.

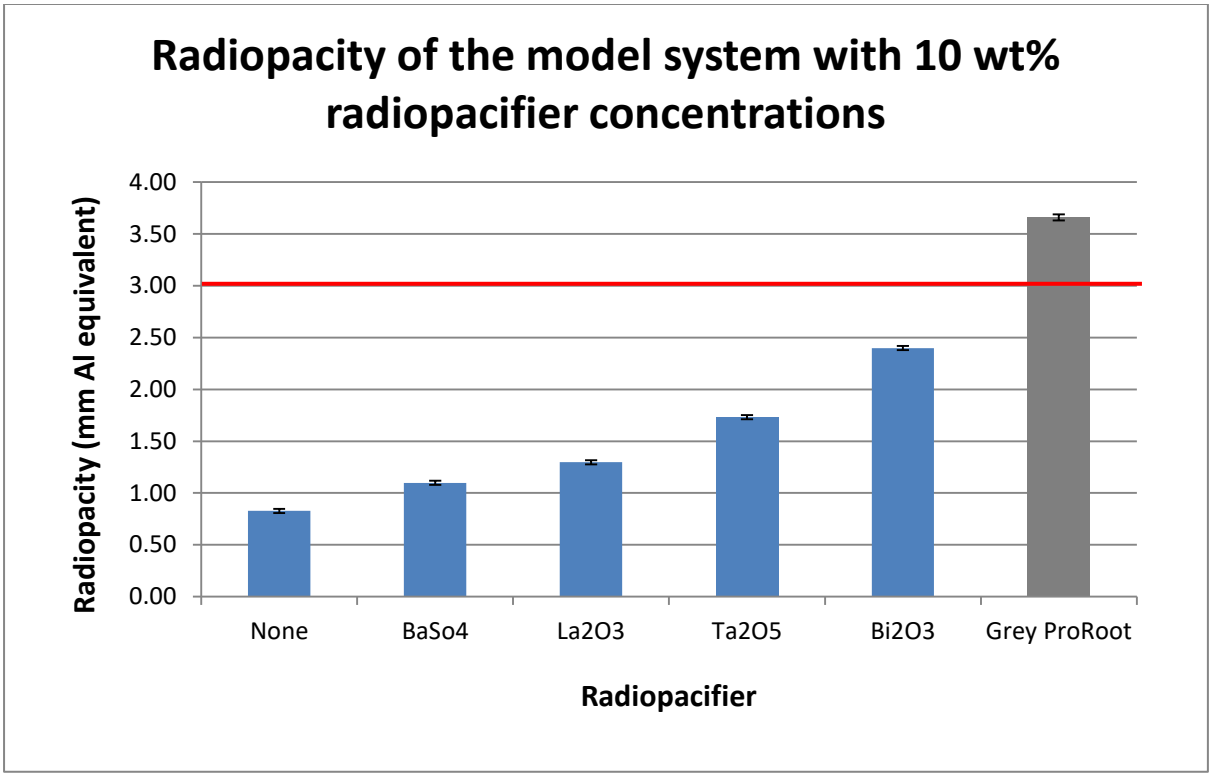

Figure 32: The radiopacity of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at 10 wt%; the model system with no radiopacifier and grey ProRoot™ MTA were used as controls. Only the commercial MTA control met the minimum ISO standard requirement of 3mm Al (red line). All cement groups were significantly different ($p < 0.05$) from each other; the commercial control was significantly different ($p < 0.01$) from all other cement groups.

At 10 wt%, all radiopacifiers tried in the model system produced cements that were insufficient to attain the ISO standard requirement of 3 mmAl. Bi_2O_3 was the radiopacifier that yielded the greatest radiopacity (2.40 mmAl), followed by Ta_2O_5(1.73 mmAl), La_2O_3(1.30 mmAl) and $BaSO_4$ (1.10 mmAl). The radiopacifier-free cement had the lowest radiopacity of 0.83 mmAl. The grey ProRoot™ control achieved a radiopacity of 3.66 mmAl, with its fixed 20 wt% content of Bi_2O_3. See Figure 32.

3.2.6 The effect of radiopacifiers on material properties of an MTA-like cement at 20 wt%

With the 20 wt% addition of radiopacifiers, the compressive strength of the radiopacifier-free model system decreased from 68MPa to 44MPa for Bi_2O_3, and 43MPa for Ta_2O_5. The addition of La_2O_3 decreased the model system compressive strength to 28 MPa, and $BaSO_4$ a further reduction to 26 MPa. The control - commercial grey ProRoot™ MTA - had a compressive strength of 34MPa, with a fixed radiopacifier content of 20 wt% Bi_2O_3. See Figure 33.

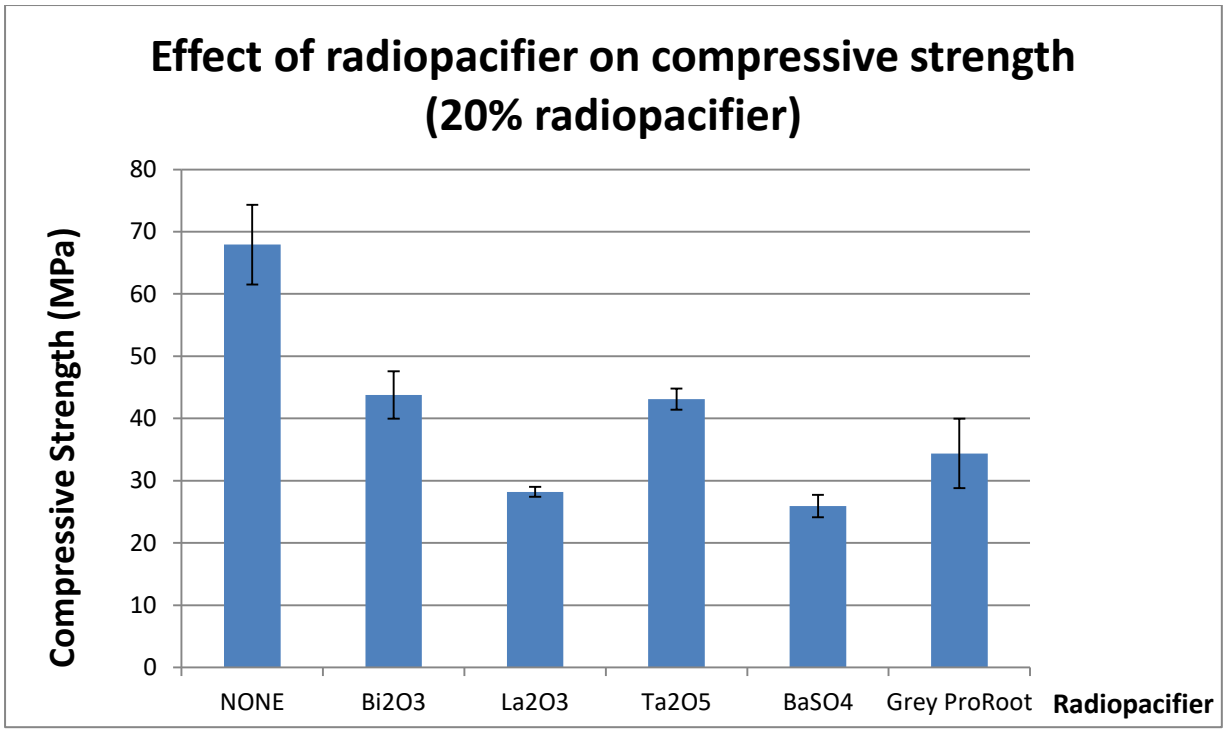

Figure 33: The compressive strength of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at 20 wt%; the model system with no radiopacifier and grey ProRoot™ MTA were used as controls. In comparison with the other groups, the CS of Bi_2O_3 and Ta_2O_5 cements were significantly different ($p < 0.05$), along with the no radiopacifier cement ($p < 0.01$).

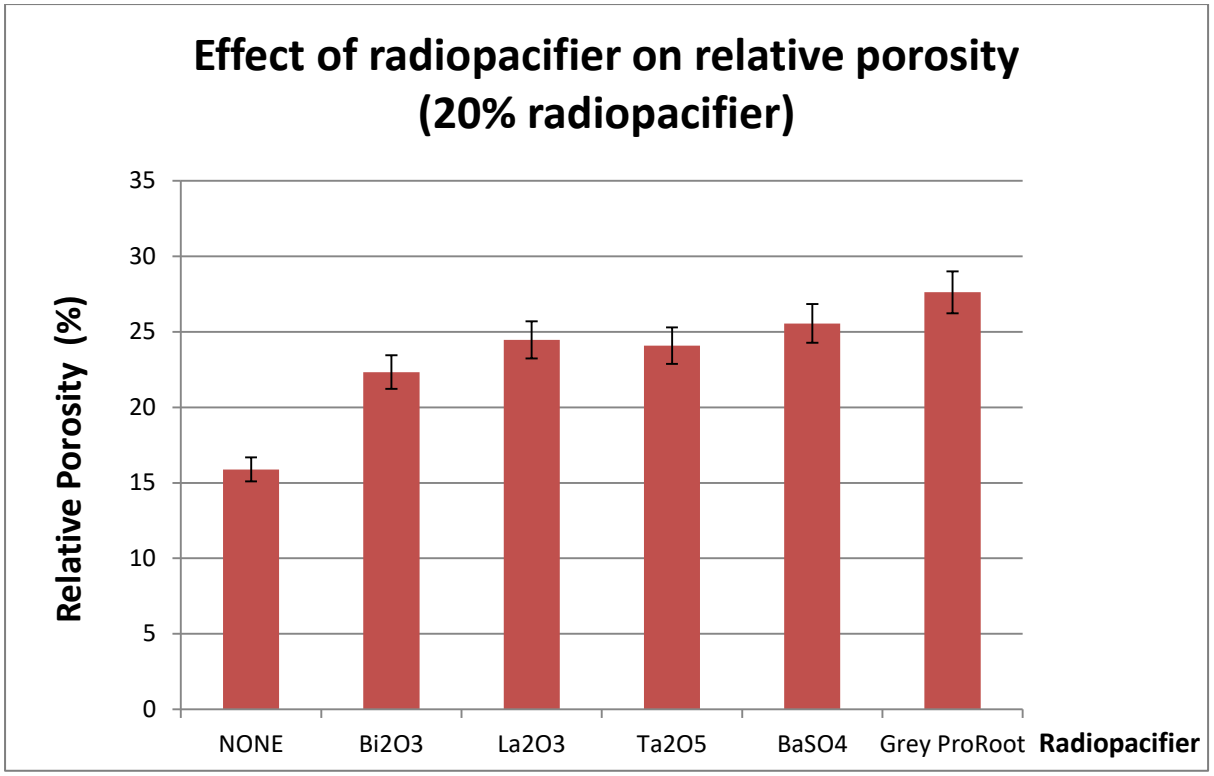

Figure 34: The relative porosity of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at 20 wt%; the model system with no radiopacifier and grey ProRoot™ MTA were used as controls. RP of Bi_2O_3 is significantly different ($p < 0.05$) from $BaSO_4$ and the control cements. The control cement without radiopacifier is significantly different ($p < 0.01$) from all other cements tested.

With regards to relative porosity in the 20 wt% cements, relative porosity increased from 16% to 22% with the addition of the radiopacifier Bi_2O_3. Ta_2O_5 and La_2O_3 addition both took the relative porosity of the model system to 24%. $BaSO_4$ as a radiopacifier produced the model system with the highest relative porosity (26%). The grey ProRoot™ control had the highest relative porosity of all the cements tested (27%). See Figure 34.

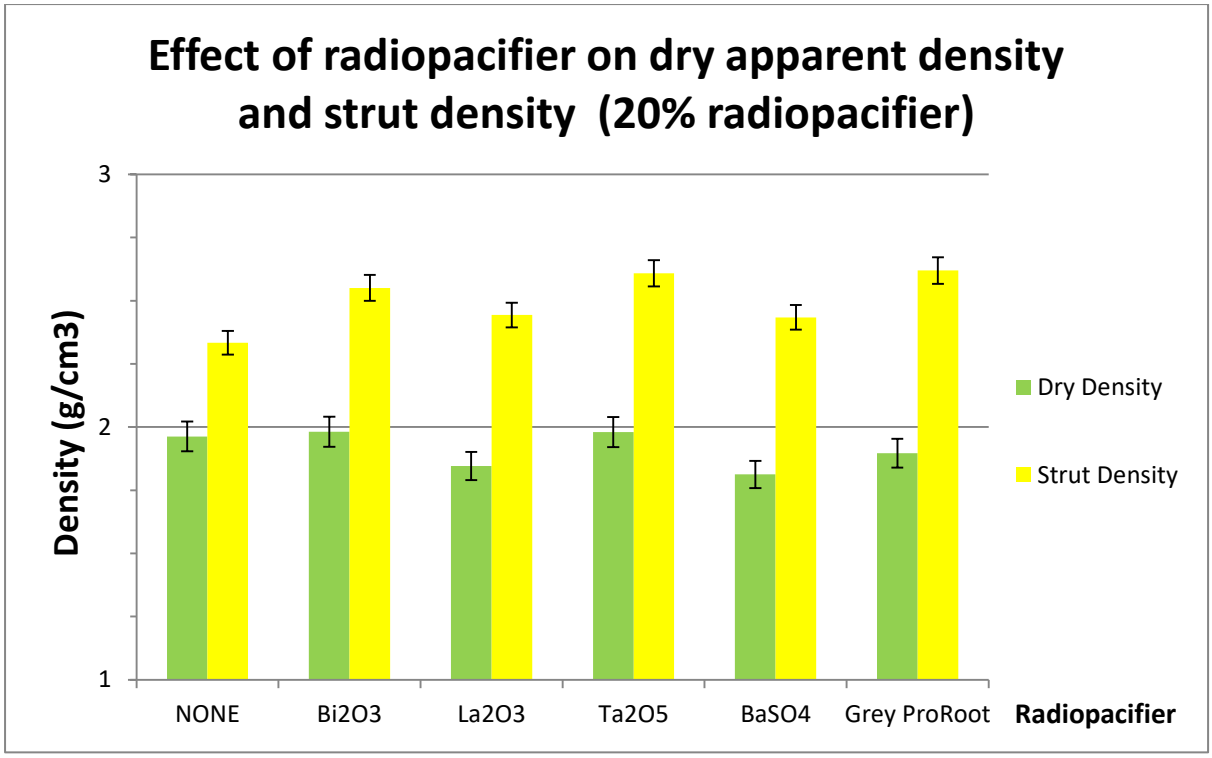

Figure 35: The apparent dry densities and strut densities of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at 10 wt%; the model system with no radiopacifier and grey ProRoot™ MTA were used as controls. The strut density of the radiopacifier-free control were significantly different from those of the other cements tested ($p < 0.05$).

As with the 10 wt% radiopacifier cements, the strut densities of the 20 wt% radiopacifier cements were greater than their dry densities, and strut density increased with the addition of all radiopacifiers. The addition of Ta_2O_5 as a radiopacifier produced a cement with the greatest strut density (2.61 g/cm^3) followed by Bi_2O_3 (2.55 g/cm^3), La_2O_3(2.44 g/cm^3) and $BaSO_4$(2.43 g/cm^3). The grey ProRoot™ control had the highest strut density of all the cements (2.62 g/cm^3). See Figure 35.

With the 20 wt% radiopacifier cements, the apparent dry densities of both Bi_2O_3- and Ta_2O_5-containing model systems were the highest values (both 1.98 g/cm^3), again closely followed by the 0 wt% radiopacifier model system (1.96 g/cm^3). The La_2O_3- and $BaSO_4$-

containing cements had lower apparent dry densities of 1.85 g/cm^3 and 1.81 g/cm^3 respectively. The grey ProRoot™ MTA control had an apparent dry density of 1.90 g/cm^3.

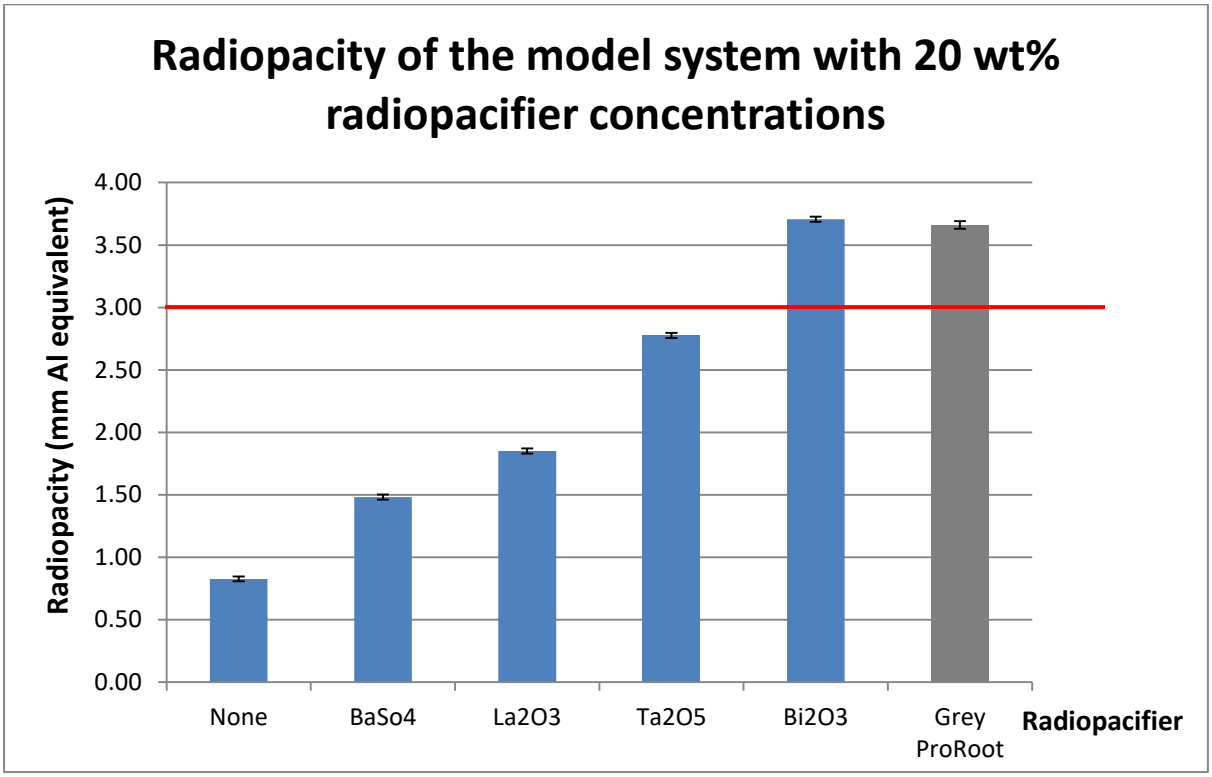

Figure 36: The radiopacity of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at 20 wt%; the model system with no radiopacifier and grey ProRoot™ MTA were used as controls. The model system with 20 wt% Bi_2O_3 and commercial MTA control were the only cements to meet the minimum ISO standard requirement of 3mm Al (red line). All groups were significantly different ($p < 0.05$) from each other, apart from the commercial control and Bi_2O_3 cement.

At 20 wt%, the only model system able to achieve the ISO standard requirement of 3 mmAl contained Bi_2O_3 (3.71 mmAl); all the other radiopacifiers tried in the model system were insufficient. The Ta_2O_5-containing model system had the second greatest radiopacity (2.78 mmAl), followed by La_2O_3 (1.85 mmAl) and $BaSO_4$ (1.48 mmAl). The radiopacifier-free cement had the lowest radiopacity of 0.83 mmAl. The grey ProRoot™ control achieved a radiopacity of 3.66 mmAl. See Figure 36.

3.2.7 The effect of radiopacifiers on material properties of an MTA-like cement at varying concentrations

The model system without radiopacifier produced the cement with the highest compressive strength (68 MPa); at 10 wt% compressive strength of the model system reduced (30-46 MPa), and this was decreased further when radiopacifier content was increased to 20 wt% (26-44 MPa). See Figure 37.

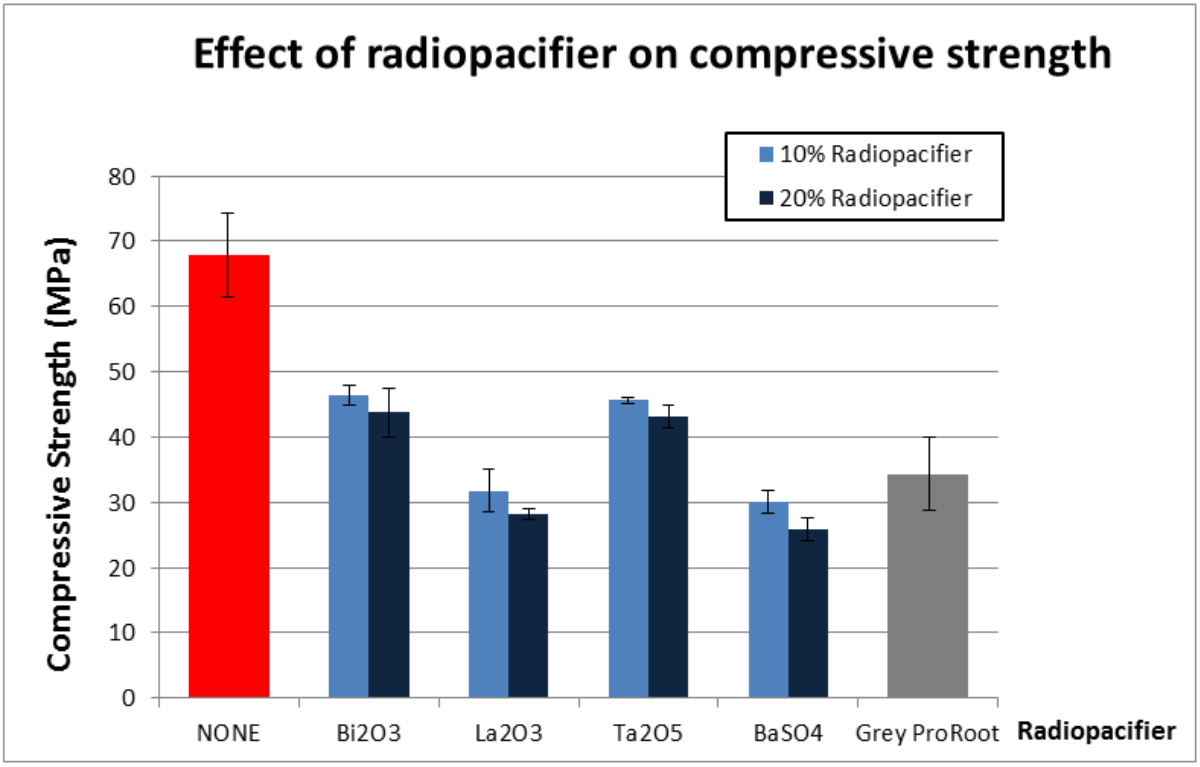

Figure 37: The compressive strength of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at both 10 and 20 wt%; the model system with no radiopacifier (red bar) and grey ProRoot™ MTA (grey bar) were used as controls. CS of Bi_2O_3 and Ta_2O_5 significantly different ($p < 0.05$) from other cements though not each other. CS of La_2O_3 and $BaSO_4$ significantly different ($p < 0.05$) from other cements though not each other.

With regards to relative porosity, the model system without radiopacifier produced the cement with the lowest relative porosity (16%). When 10 wt% radiopacifier was added, the relative porosity of the cements increased (to 20-25%); a further increase in porosity was observed when radiopacifier content increased to 20 wt%. Only a very small change in relative porosity was evident between 10 wt% and 20 wt% $BaSO_4$ addition sample groups (25% to 26%), compared to the other model system cements which had a more pronounced increase. See Figure 38.

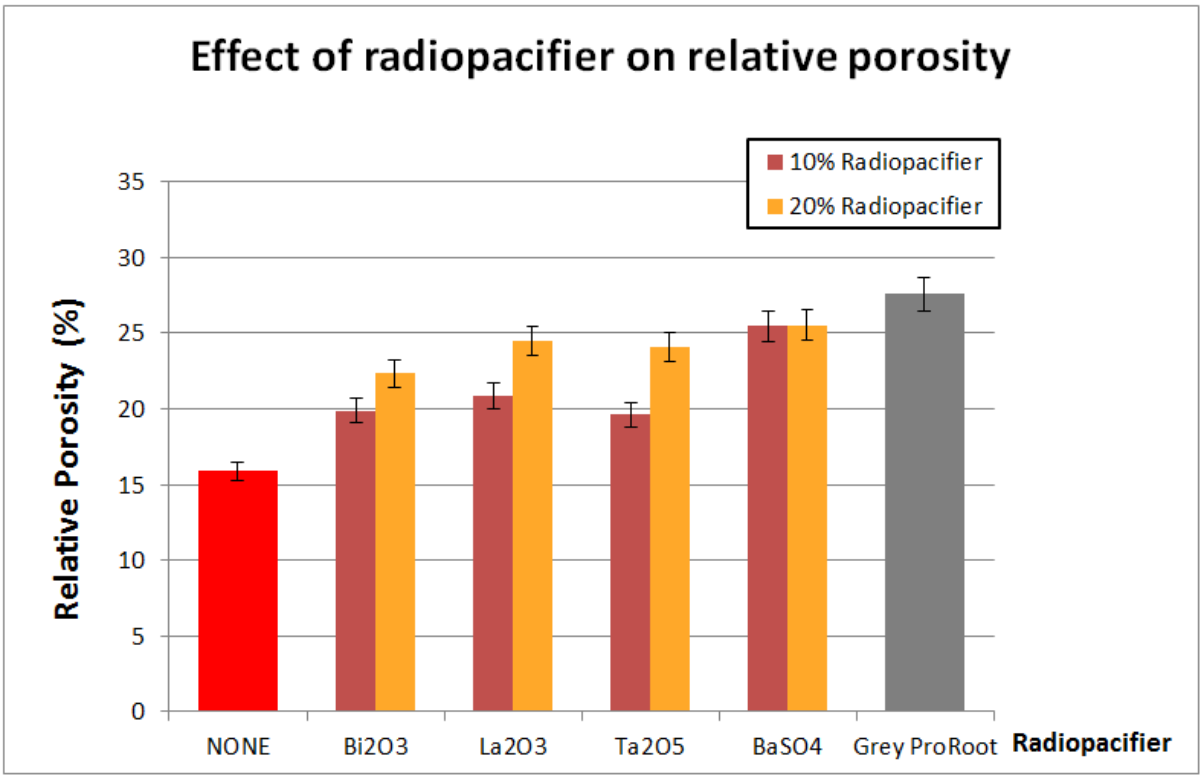

Figure 38: The relative porosity of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at 10 and 20 wt%; the model system with no radiopacifier (red bar) and grey ProRoot™ MTA (grey bar) were used as controls. At 10 wt%, RP of $BaSO_4$ was significantly different ($p < 0.05$) to the other cements. At 20 wt%, RP of Bi_2O_3 was significantly different ($p < 0.05$) to the other cements.

In all cements tested, strut densities were always greater than apparent dry densities. The model system without radiopacifier produced the cement with the lowest strut density (2.33 g/cm^3). The addition of 10 wt% radiopacifier increased the strut density of all cements (2.42 – 2.46 g/cm^3), and 20 wt% radiopacifier addition increased the strut density further (2.43 – 2.55 g/cm^3).

Apparent dry densities increased with the addition of Bi_2O_3 and Ta_2O_5, however decreased with the addition of La_2O_3 and $BaSO_4$. All apparent dry densities of cements with radiopacifier additions marginally increased with the increment of the radiopacifier from 10 wt% to 20 wt%. See Figure 39.

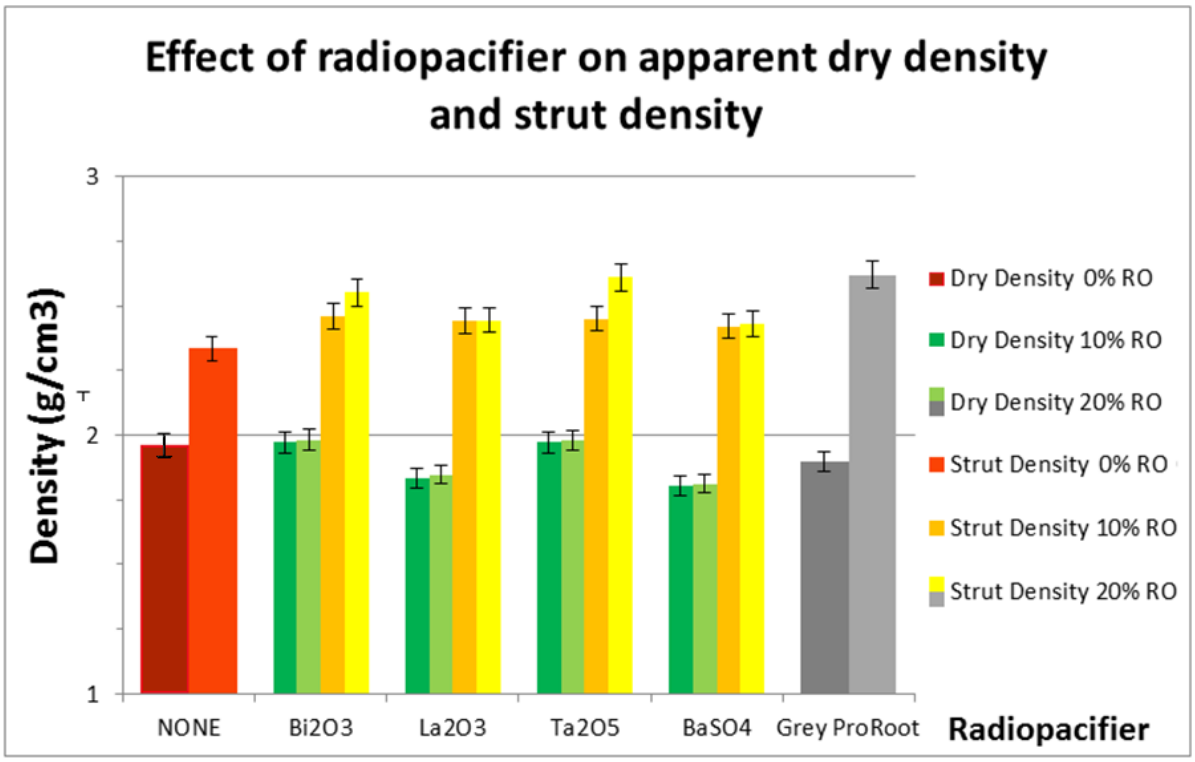

Figure 39: The apparent dry density and strut density of the model system with various radiopacifiers (Bi_2O_3, La_2O_3, Ta_2O_5, $BaSO_4$) at 10 and 20 wt%; the model system with no radiopacifier (red bar) and grey ProRoot™ MTA (grey bar) were used as controls. Dry density of Bi_2O_3,Ta_2O_5 and the radiopacifier-free cement significantly different ($p < 0.05$) from other cements though not each other. Dry density of La_2O_3 and $BaSO_4$ significantly different ($p < 0.05$) from other cements though not each other.

3.3 The effect of bismuth oxide on MTA

3.3.1 The effect of bismuth oxide on the compressive strength of MTA-like cements

The model system, comprising no Bi_2O_3, had the highest compressive strength at 82 MPa, which decreased to 40 MPa when 10 wt% Bi_2O_3 was added; this gradually decreased further to 29 MPa, as the Bi_2O_3 content increased to 40 wt% Bi_2O_3. See Figure 40. An inverse relationship was evident between bismuth oxide concentration and cement compressive strength.

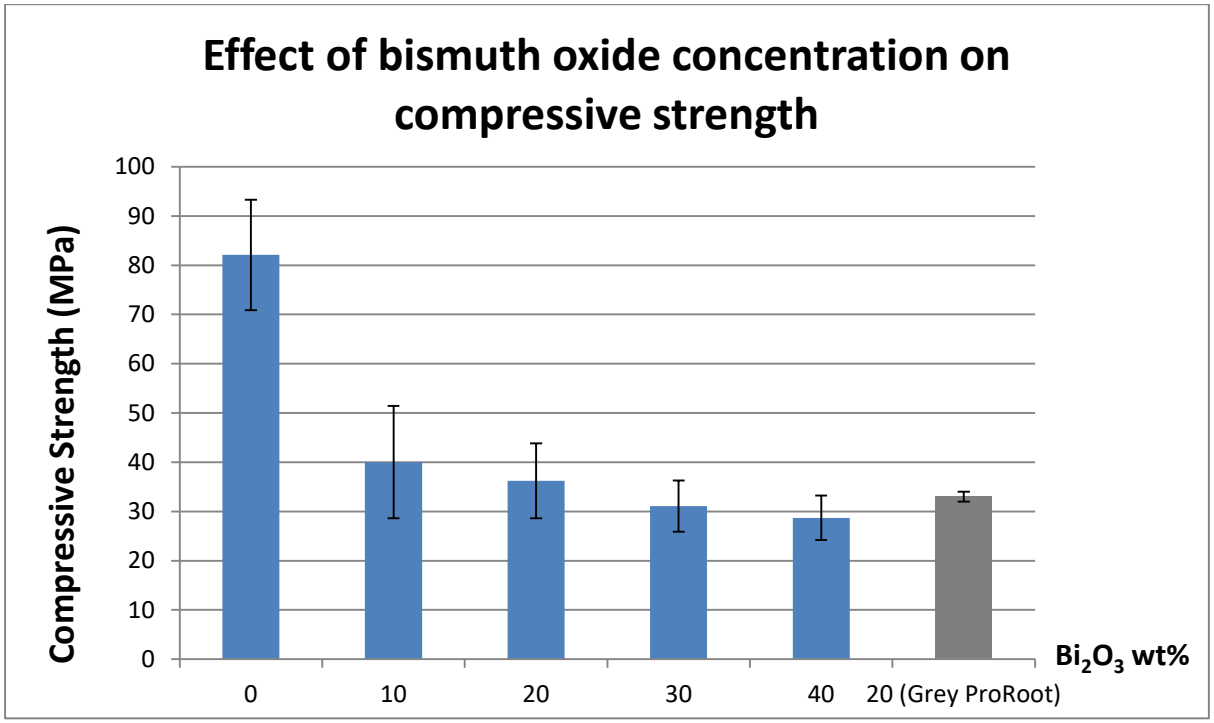

Figure 40: The compressive strength of different MTA-like cement systems with various concentrations of Bi_2O_3, showing an inverse relationship. ProRoot™ MTA was used as a control (grey bar). CS of Bi_2O_3–free cement significantly different ($p < 0.05$) to the other cements.

The commercial MTA control had a strength of 33 MPa compared to the 36 MPa of the model system, both with 20 wt% Bi_2O_3. All compressive strengths for Bi_2O_3 containing samples of the model system and the control were not significantly different to each other, but there was a clear trend.

3.3.2 The effect of bismuth oxide on the relative porosity of MTA-like cements

The relative porosity of the cement systems increased with increasing Bi_2O_3 content of the model system from 15 % for 0 wt% to 31 % for 40 wt% Bi_2O_3. See Figure 41. A linear relationship was evident between bismuth oxide concentration and cement relative porosity.

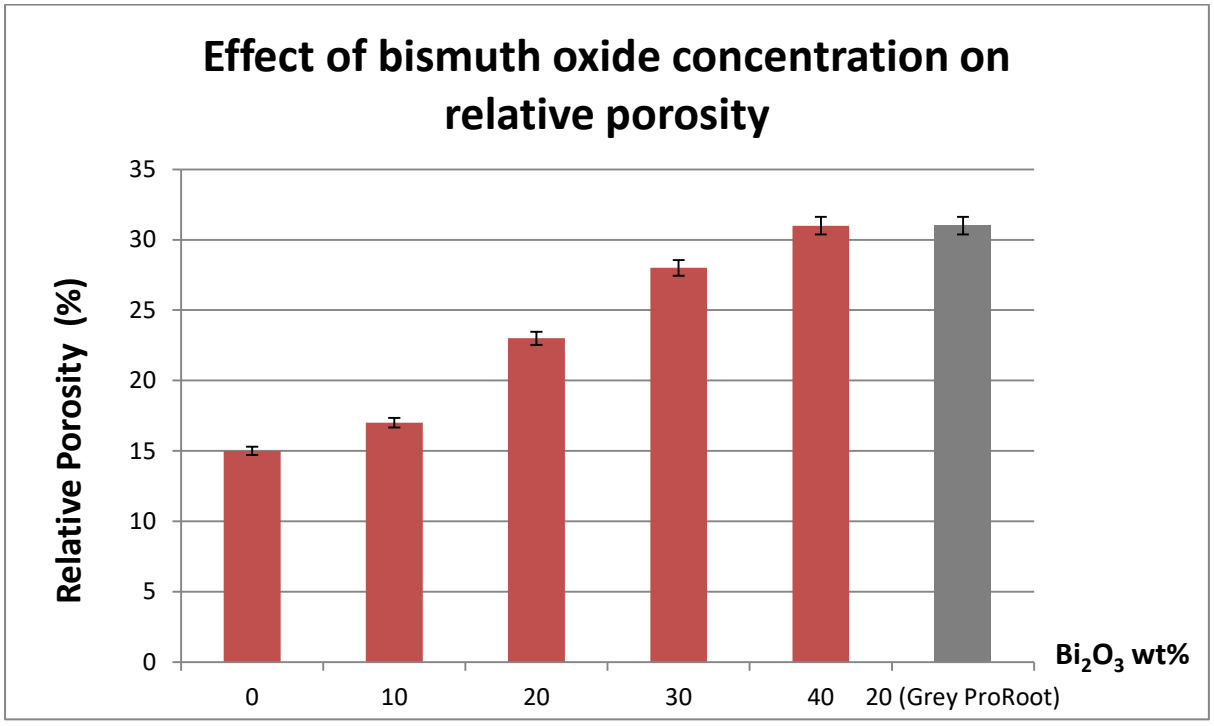

Figure 41: The relative porosity of different MTA-like cement systems with various concentrations of Bi_2O_3, showing a linear relationship. ProRoot™ MTA was used as a control (grey bar). RP of all cements significantly different ($p < 0.05$) from each other except commercial control vs 40 wt% Bi_2O_3.

Commercial MTA had a relative porosity of 31 % compared to 23 % of the 20 wt% Bi_2O_3 model system. All relative porosities, apart from the model system with 40 wt% Bi_2O_3 and the MTA control, were significantly different ($p < 0.05$).

3.3.3 The effect of bismuth oxide on the density of MTA-like cements

As expected, all apparent dry densities were found to be less than the strut densities in the cement model system variations and commercial MTA. See Figure 42. In the model system, both the apparent dry density and strut density increased with increasing Bi_2O_3 content; from 2.02 g/cm^3 and 2.38 g/cm^3 for 0 wt% to 2.23 g/cm^3 and 3.22 g/cm^3 for 40 wt% Bi_2O_3, respectively, displaying a linear relationship. Commercial MTA had both its apparent dry density and strut density (1.89 g/cm^3 and 2.74 g/cm^3 respectively) less than those found for the comparable 20 wt% Bi_2O_3 model system (2.12 g/cm^3 and 2.76 g/cm^3 respectively).

All apparent dry densities, apart from the model system with 20 or 30 wt% Bi_2O_3, were significantly different ($p < 0.05$). All strut densities, apart from the model system with 20 wt% Bi_2O_3 and the MTA control were significantly different from each other ($p < 0.05$). For reference, the specific density of the Portland cement used (Mastercrete) and Bi_2O_3 powders were measured, and found to be 3.13 ± 0.02 g/cm^2 and 8.86 ± 0.02 g/cm^2, respectively.

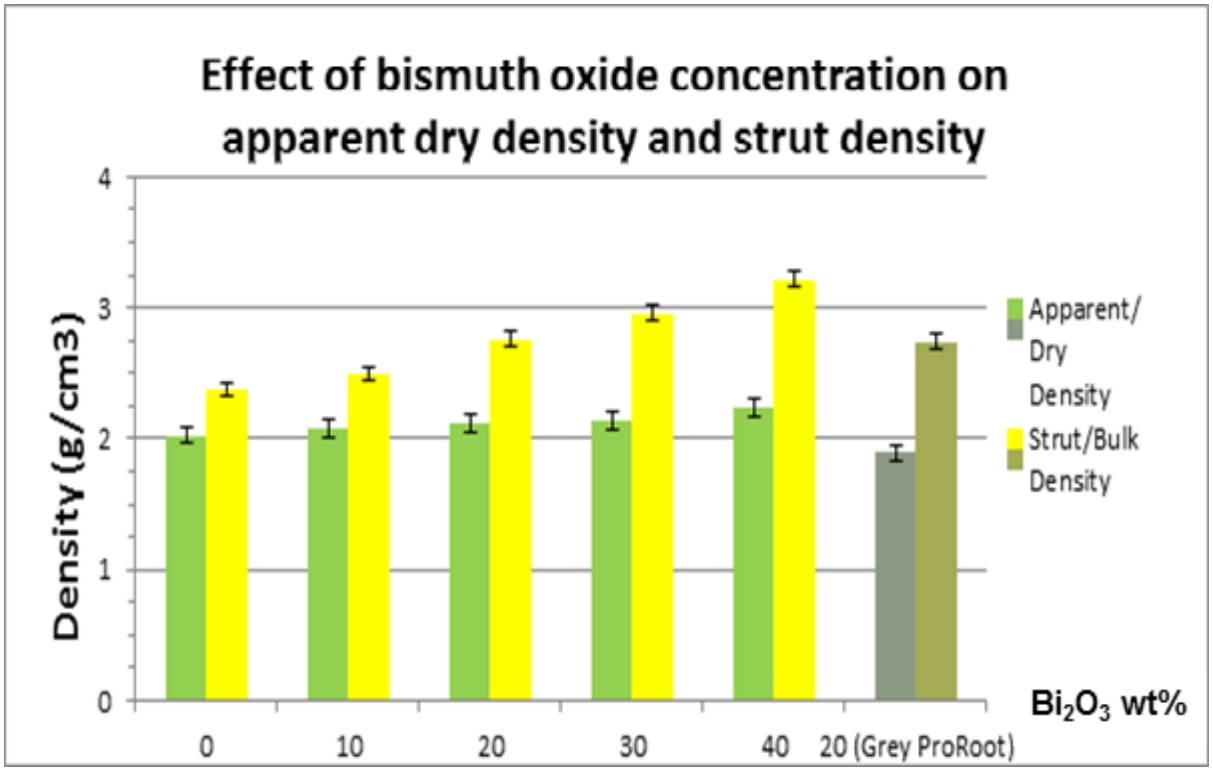

Figure 42: The apparent dry densities and strut densities of different MTA-like cement systems with various concentrations of Bi_2O_3, showing a linear relationship. ProRoot™ MTA was used as a control (shaded bars). Strut density of 20 wt% Bi_2O_3 significantly different ($p < 0.05$) to all cements except the commercial control. Strut density of 30 wt% and 40 wt% Bi_2O_3 significantly different ($p < 0.05$) to all cements and each other.

3.3.4 The relationship of bismuth oxide to the material properties of MTA-like cements

Strong linear correlationships between increasing Bi_2O_3 content and strut density ($R^2 = 0.99$), dry density ($R^2 = 0.96$) and relative porosity ($R^2 = 0.98$) were discovered, see Table 4. No linear relationship between increasing Bi_2O_3 content and compressive strength was found ($R^2 = 0.68$).

Table 4: Best-fit correlation (linear regression) y = a + bx between strut density, dry density, relative porosity and compressive strength as dependent variables y and Bi_2O_3 content as independent variable x. Coefficients a and b are given with their standard deviation. The squared multiple correlation R^2 is given with the significance of the p of the regression

y [x (wt % Bi2O3)]	a	b	R^2 (p)
Strut density (g/cm3)	2.336 ± 0.033	0.021 ± 0.001	0.99 (p < 0.001)
Dry density (g/cm3)	2.022 ± 0.014	0.0048 ± 0.0006	0.96 (p < 0.01)
Relative porosity (%)	14.2 ± 0.9	0.43 ± 0.04	0.98 (p < 0.01)
Compressive strength (Mpa)	61.6 ± 11.3	-0.91 ± 0.36	0.68 (p = 0.08)

3.4 The effect of PLR on the workability of an MTA-like cement

The development of consistency and handling (with perceived optimum scores being 3 and 5, respectively) for various PLRs are displayed in Figure 43 and 44. A Kruskal-Wallis analysis revealed no significant difference between each assessor for either consistency ($p = 0.476$) or handling ($p < 0.05$). Significant differences were recorded for both consistency and handling versus PLR ($p < 0.01$).

3.4.1 The effect of PLR on the consistency of an MTA-like cement

See Figure 43. Mann-Whitney tests revealed a significant improvement in the consistency of the cement paste from a PLR of 3.0 (there being perceived as too liquid) to 3.5 to 4.0 g/ml, where an ideal consistency of around 3 was approached. Consistency of the cement paste increased further to levels being perceived as too dry for PLRs of 5.0 and 5.5 g/ml. Consistency at PLR 4.0 g/ml was significantly different to all other PLRs ($p < 0.01$), while consistency at PLR 4.5 g/ml was not significantly different to PLR 5.0 g/ml ($p < 0.05$). PLRs of 3.0 and 5.5 g/ml were rated significantly as too liquid or too dry, respectively, by all assessors to provide a homogeneous cement paste ($p < 0.01$).

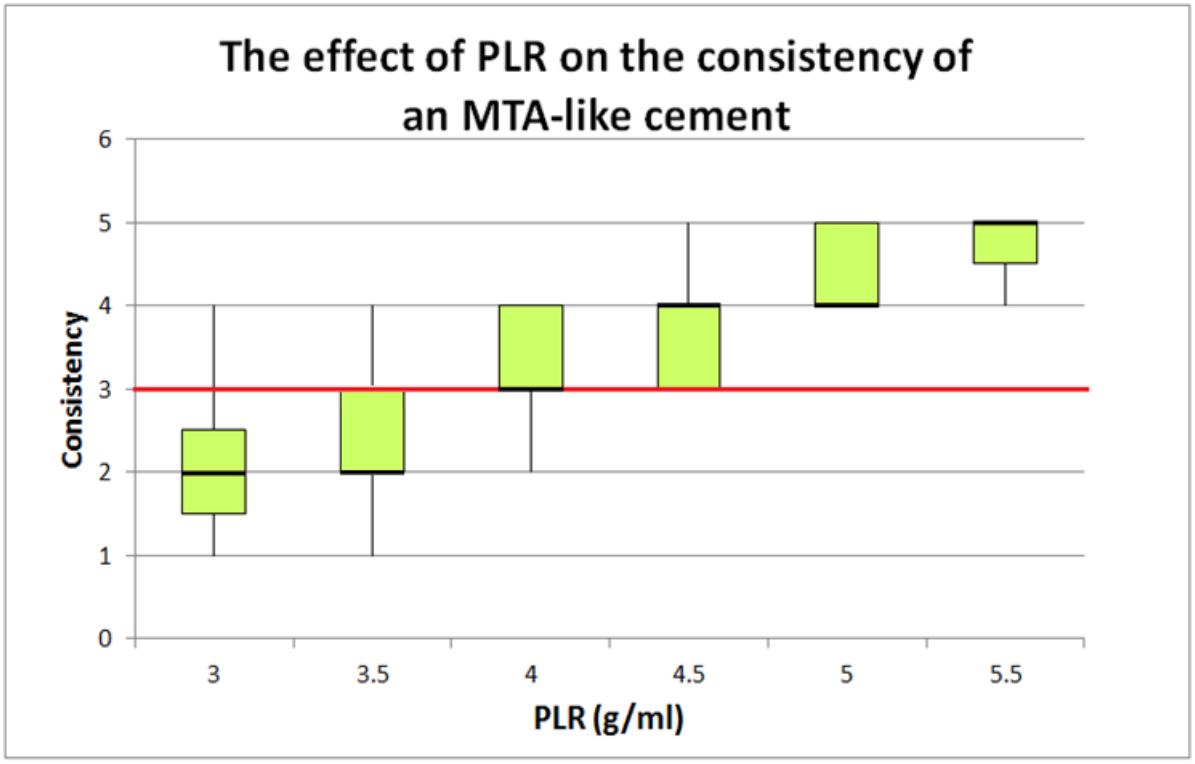

Figure 43: The perceived consistency of an MTA-like cement at various PLRs displayed as a box and whisker plot. Optimum consistency is represented by a score of 3 (red line), with 1 being too liquid and 5 being too dry. The boxes represent the interquartile range; the whiskers represent the highest and lowest scores given for the PLR; the bold line indicates the median score of the assessors

3.4.2 The effect of PLR on the handling of an MTA-like cement

Handling was the poorest at the higher PLRs of 5.0 g/ml and 5.5 g/ml and improved significantly when PLRs decreased to 4.0 g/ml and 4.5 g/ml ($p < 0.01$). See Figure 44. Handling again deteriorated at the lower PLRs of 3.0 g/ml and 3.5 g/ml, though was not perceived to be as poor as the two highest PLRs. The PLR of 5.5 g/ml was rated as being non-workable by all assessors ($p < 0.01$).

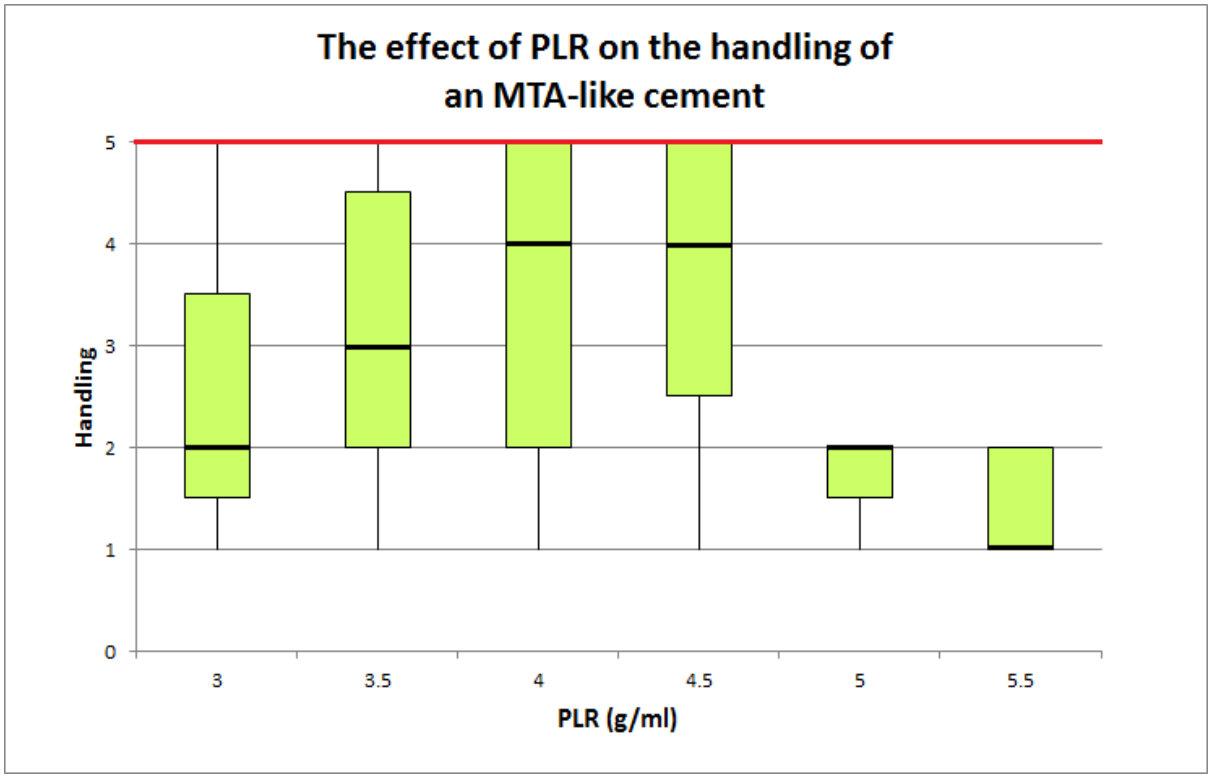

Figure 44: The perceived handling of an MTA-like cement at various PLRs displayed as a box and whisker plot. Optimum handling is represented by a score of 5 (red line) and an unworkable paste a score of 1. The boxes represent the interquartile range; the whiskers represent the highest and lowest scores given for the PLR; the bold line indicates the median score of the assessors

3.4.3 The effect of PLR on the material properties of an MTA-like cement

The compressive strength for the model system at PLR 3.0 and 3.5 g/ml increased significantly from 36.76 and 42.49 MPa, respectively, to peak at 52.31 MPa for 4.0 g/ml ($p < 0.05$) and decreased significantly to 44.74 MPa for 5.0 g/ml ($p < 0.05$). See Figure 45.

Relative porosity decreased from 23 % and 22 % for PLR 3.0 and 3.5 g/ml to 21 % for 4.0 g/ml; this then increased significantly to 26 % when raising PLR to 5.0 g/ml ($p < 0.05$). See Figure 46.

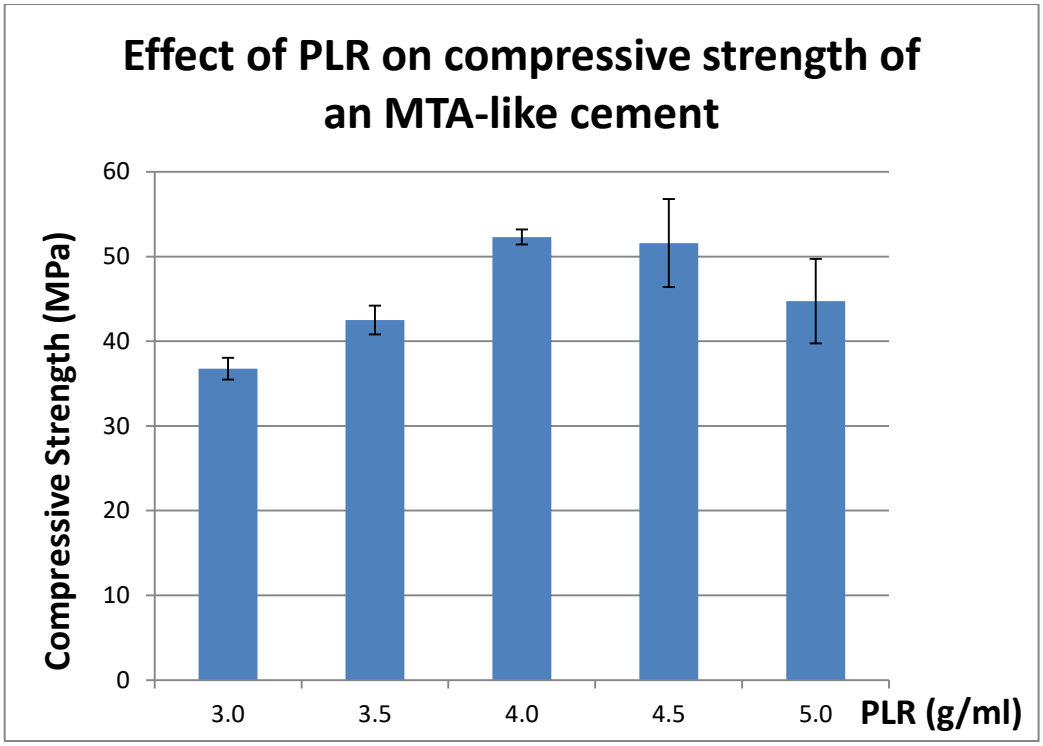

Figure 45: The effect of PLR on the compressive strength of an MTA-like cement. Peak compressive strength was found to be at 4.0 g/ml, with a lower strength at lower and higher PLRs. CS of PLR 3.0 g/ml cement significantly different ($p < 0.05$) to all other cements. CS of PLR 3.5 g/ml cement significantly different ($p < 0.05$) to all other cements except PLR 5.0 g/ml.

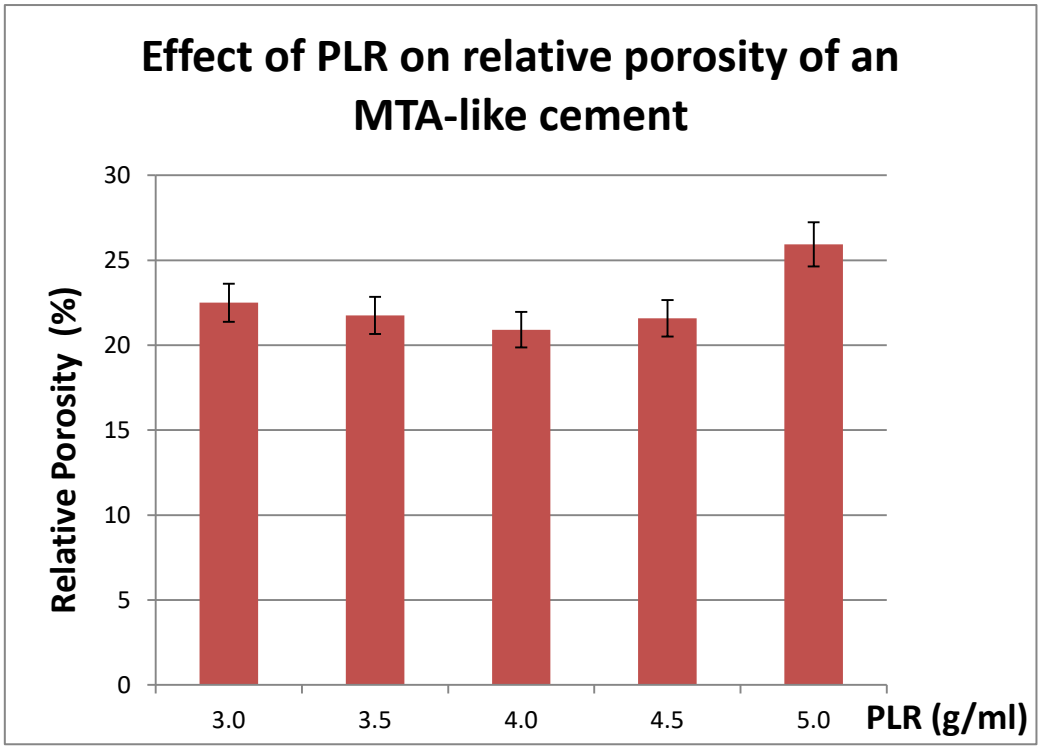

Figure 46: The effect of PLR on the relative porosity of an MTA-like cement. The lowest relative porosity was found to be at 4.0 g/ml, with a higher porosity at lower and higher PLRs. RP of PLR 5.0 g/ml cement significantly different ($p < 0.05$) to other cements.

See Table 5 for the overall comparison of the different characteristics of the model system at various PLRs. Apparent dry density increased from 2.02 and 2.05 g/cm^3 for PLR 3.0 g/ml and 3.5 g/ml, respectively, to a peak of 2.13 g/cm^3 for PLR 4.0 g/ml and decreased significantly to 1.93 g/cm^3 for PLR 5.0 g/ml ($p < 0.05$). This pattern was repeated with the recorded strut densities: PLRs 3.0 g/ml and 3.5 g/ml had strut densities of 2.61 g/cm^3 and 2.62 g/cm^3 respectively; a peak strut density was observed at PLR 4.0 g/ml (2.69 g/cm^3), with a significant decrease of density to 2.60 g/cm^3 at PLR 5.0 g/ml ($p < 0.05$).

Table 5: The wet compressive strength, relative porosity, apparent dry density and strut density of cement samples with increasing PLR of the model system. Either the standard deviation or minimum error of method are given for mean values.

75MC-20BO-5POP PLR	Compressive Strength (MPa)	Relative Porosity (%)	Dry Density (g/cm3)	Strut Density (g/cm3)
3.0	36.76 ± 3.44	22.50 ± 1	2.02 ± 0.02	2.61 ± 0.02
3.5	42.49 ± 4.62	21.75 ± 1	2.05 ± 0.02	2.62 ± 0.02
4.0	52.31 ± 2.45	20.90 ± 1	2.13 ± 0.02	2.69 ± 0.02
4.5	51.59 ± 13.72	21.58 ± 1	2.09 ± 0.02	2.67 ± 0.02
5.0	44.74 ± 13.33	25.93 ± 1	1.93 ± 0.02	2.60 ± 0.02

3.5 The effect of cement paste dilution on the radiopacity of MTA

All 6 MTA cement systems were assessed with regard to their radiopacity at varying PLRs as described in 2.2.4. The minimum radiopacity of 3 mmAl was considered as the acceptable radiographic threshold for all the cements tested, as specified by the standard for dental root canal sealing materials (ISO 6876:2001).

3.5.1 The effect of PLR on the radiopacity of grey MTA (Dentsply)

gMTA[D] remained above the required 3mm radiopacity for all PLRs tested. Its lowest radiopacity was observed at the lowest PLR of 2.0 g/ml (3.95 mmAl). Radiopacity rose incrementally to peak at the highest PLR of 5.5 g/ml (5.17 mmAl). The data points followed a shallow curve trend line with a good fit ($R^2 = 0.97$). See Figure 47.

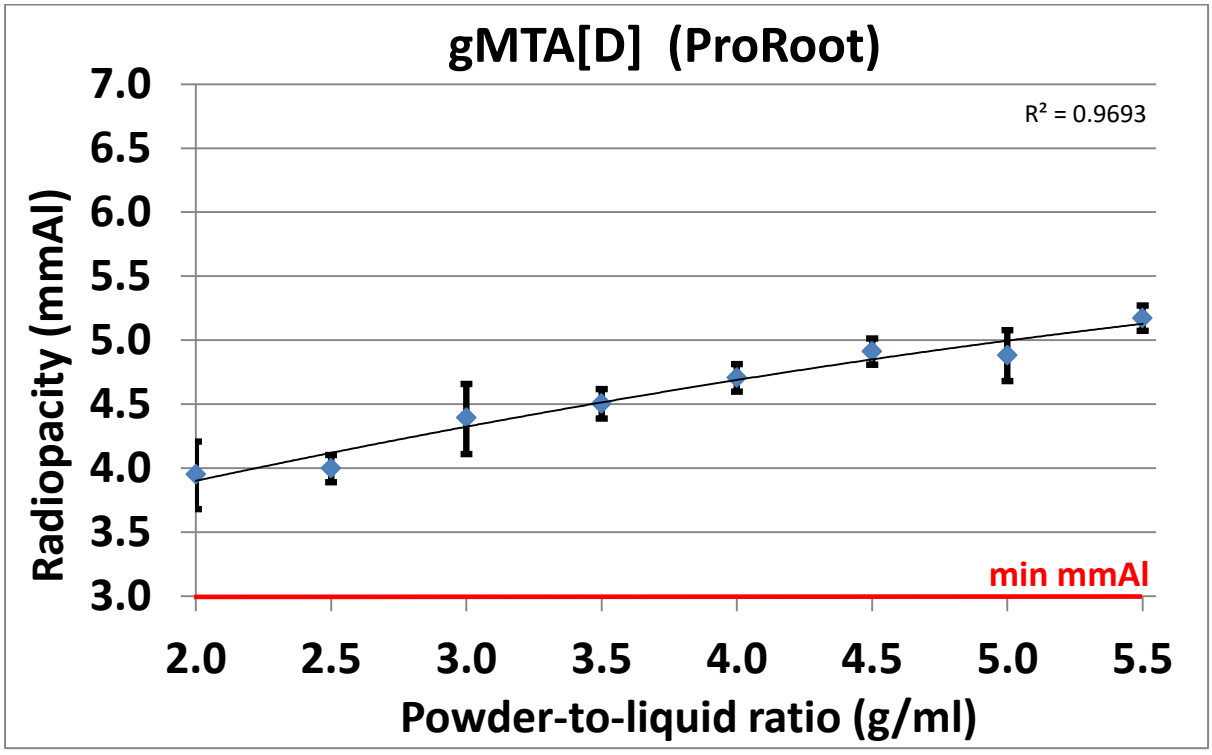

Figure 47: The radiopacity of Dentsply grey MTA (ProRoot™) at various levels of PLR. All samples achieved the 3 mmAl minimum standard (red line)

3.5.2 The effect of PLR on the radiopacity of white MTA (Dentsply)

wMTA[D] also remained above the minimum threshold value and its lowest radiopacity was at the lowest PLR of 2.0 g/ml (3.81 mmAl). Its peak radiopacity was at PLR 4.5 g/ml (5.77 mmAl), and declined at PLRs greater than 4.5 g/ml. The data points followed a relatively shallow trend line with a good fit (R^2 = 0.82). See Figure 48.

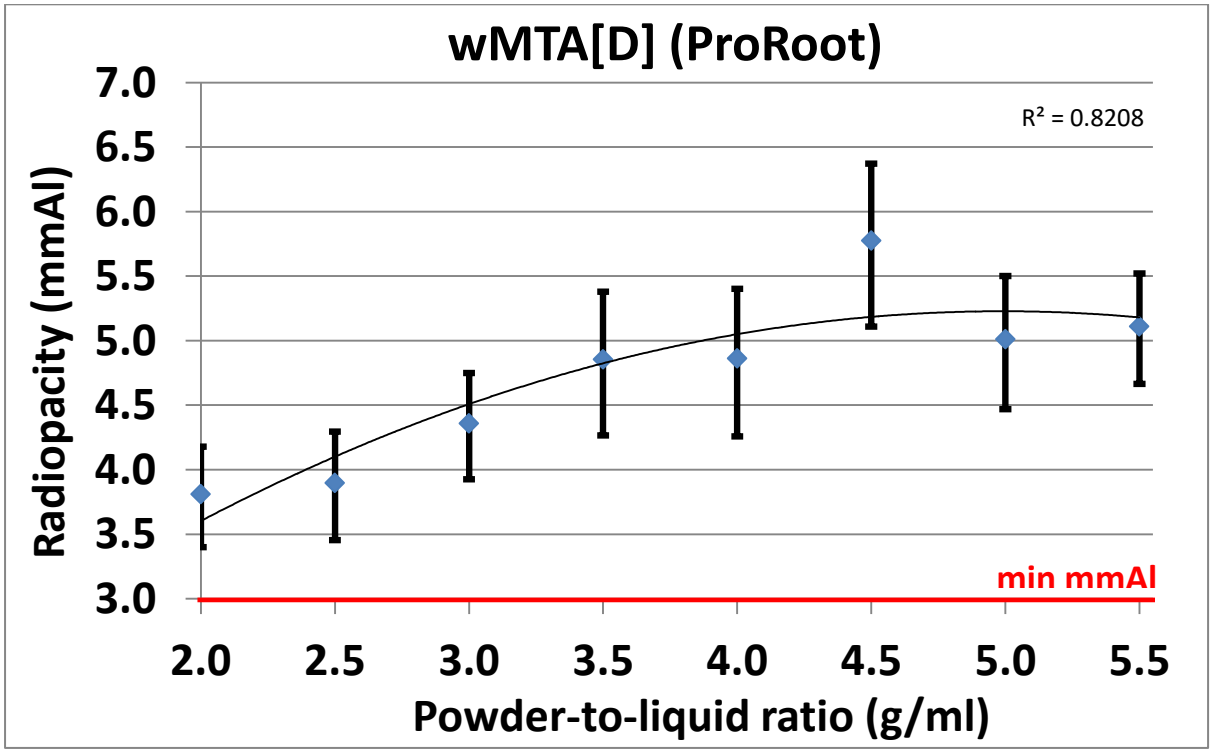

Figure 48: The radiopacity of Dentsply white MTA (ProRoot™) at various levels of PLR. All samples achieved the 3 mmAl minimum standard (red line)

3.5.3 The effect of PLR on the radiopacity of grey MTA (Angelus®)

gMTA[A] met the minimum radiopacity requirement for all levels of PLRs investigated. Lowest radiopacity was observed at 2.5 g/ml (4.35 mmAl), although the sample at PLR 2.0 g/ml yielded a radiopacity of 4.46 mmAl, of which the difference was not statistically significant. The data points followed a steeper trend line with a good fit (R^2 = 0.92); PLR 5.0 g/ml gave the greatest radiopacity for the cement (6.25 mmAl), before it declined again. See Figure 49.

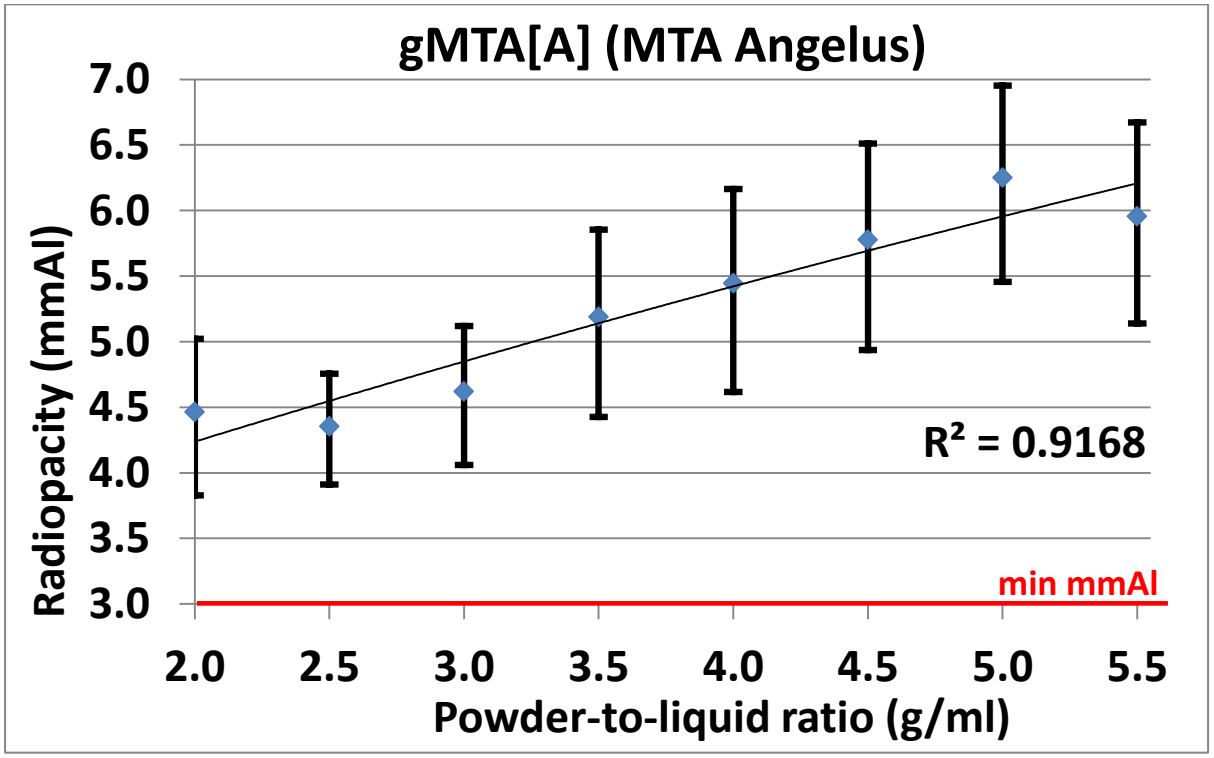

Figure 49: The radiopacity of Angelus® grey MTA (MTA Angelus®) at various levels of PLR. All samples achieved the 3 mmAl minimum standard (red line)

3.5.4 The effect of PLR on the radiopacity of white MTA (Angelus®)

wMTA[A], although with all samples satisfying the 3 mmAl minimum requirement, came very close to the minimum radiopacity requirement at PLR 2.0 g/ml (3.44 mmAl). Peak radiopacity was at PLR 4.5g/ml (5.19 mmAl). The data points followed a relatively steep curve with a good coefficient of determination (R^2 = 0.89). See Figure 50.

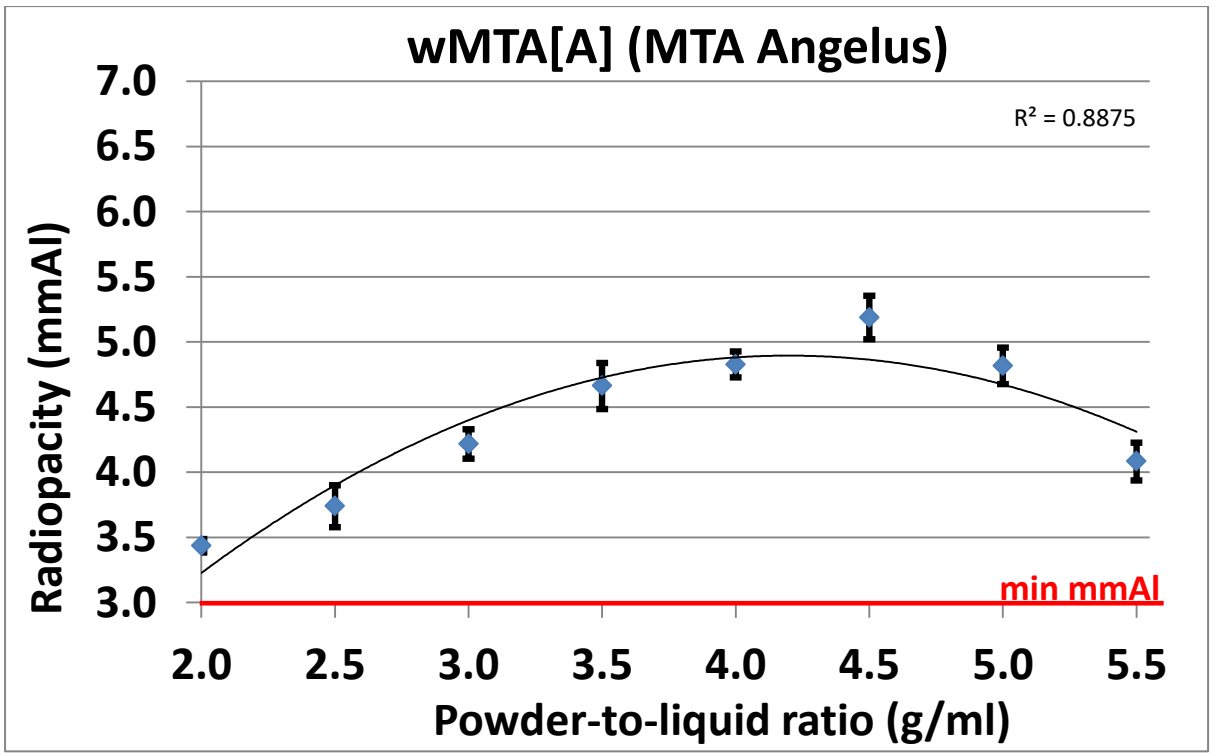

Figure 50: The radiopacity of Angelus® white MTA (MTA Angelus®) at various levels of PLR. All samples achieved the 3 mmAl minimum standard (red line)

3.5.5 The effect of PLR on the radiopacity of grey MTA (Model System)

gMTA[MS] also met the minimum radiopacity requirement however came very close to the minimum radiopacity requirement at its lowest PLR 2.0 g/ml (3.33 mmAl). Peak radiopacity was at PLR 5.0 g/ml (4.98 mmAl). The best fit trendline had a strong match with the data points ($R^2 = 0.97$). See Figure 51.

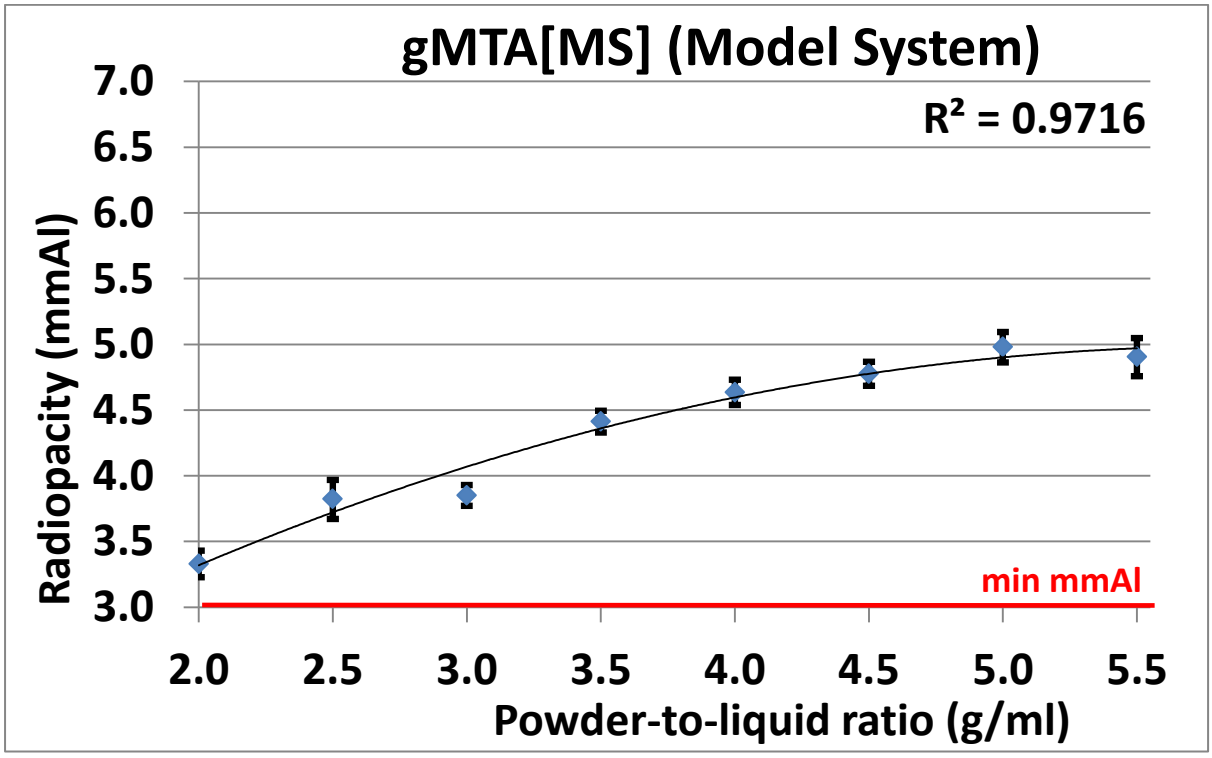

Figure 51: The radiopacity of grey MTA Model System at various levels of PLR. All samples achieved the 3 mmAl minimum standard (red line); a polynomial regression trendline was drawn with a good fit ($R^2 = 0.97$)

3.5.6 The effect of PLR on the radiopacity of white MTA (Model System)

wMTA[MS] again satisfied the minimum radiopacity of 3 mmAl for all of its samples. See Figure 52. The lowest PLR 2.0 g/ml sample had the poorest radiopacity level (3.45 mmAl), which was very close to the standard requirement. The data points followed a shallow curve with a good correlation to its trend line (R^2 = 0.97). Peak radiopacity was at PLR 5 g/ml (4.57 mmAl).

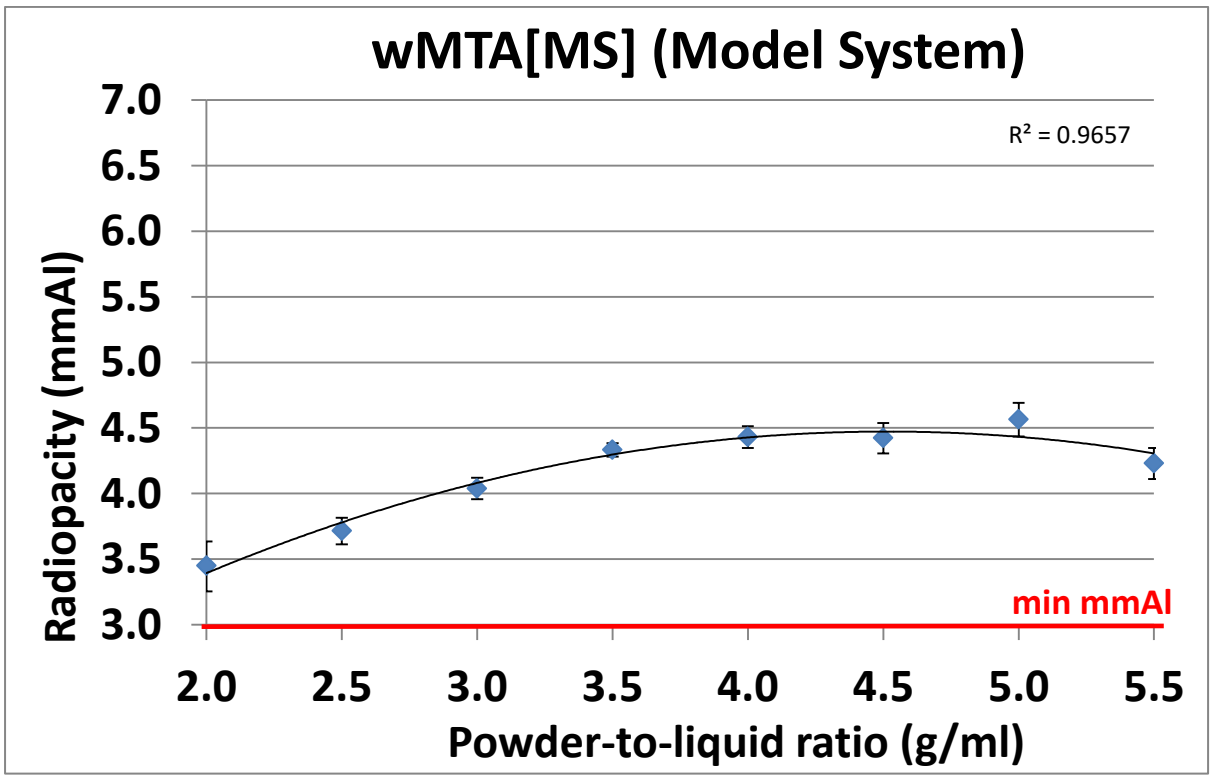

Figure 52: The radiopacity of white MTA Model System at various levels of PLR. All samples achieved the 3 mmAl minimum standard (red line); a polynomial regression trendline was drawn with a good fit (R^2 = 0.97)

3.5.7 Overview of the effect of PLR on the radiopacity of MTA cements

The radiopacity, strut density and relative porosity of each MTA cement system, mixed at the recommended PLR of 3.0 g/ml, are presented in Table 6. Of the commercial cements, gMTA[A] was the most radiopaque (4.62 mmAl) and wMTA[A] the least (4.22 mmAl). gMTA[MS] was overall the least radiopaque cement tested (3.85 mmAl). With regards to the specific material density of the cements, gMTA[A] was the most dense (2.75 g/cm^3); the two commercial white MTAs were the least (2.62 g/cm^3). The cement with the highest relative porosity was wMTA[A] (34%) and the lowest was wMTA[D] (16%). The cements with the higher strut densities and lower relative porosities tended to have a greater overall radiopacity.

Table 6: Radiopacity, strut density and relative porosity of grey and white versions of both commercial MTA and the model system. Either the standard deviation or minimum error of method are given for mean values.

MTA Cement	Radiopacity (mm Al)	Strut Density (g/cm3)	RP (%)
gMTA[D]	**4.39 ± 0.28**	**2.74 ± 0.02**	**31 ± 1**
wMTA[D]	**4.36 ± 0.41**	**2.62 ± 0.02**	**16 ± 1**
gMTA[A]	**4.62 ± 0.53**	**2.75 ± 0.02**	**22 ± 1**
wMTA[A]	**4.22 ± 0.12**	**2.62 ± 0.02**	**34 ± 1**
gMTA[MS]	**3.85 ± 0.08**	**2.67 ± 0.02**	**28 ± 1**
wMTA [MS]	**4.04 ± 0.08**	**2.73 ± 0.02**	**33 ± 1**

The overall highest radiopacity reading obtained was from gMTA[A] at PLR 5.0 g/ml (6.25 mmAl); this was also the PLR for the optimal radiopacity for both gMTA[MS] (4.98 mmAl) and wMTA[MS] (4.57 mmAl). gMTA[D] reached its higest radiopacity level (5.17mmAl) when mixed at the maximum PLR of 5.5g/ml, though this was the lowest overall peak radiopacity of all commercial cements tested. Both commercial white MTAs tested exhibited a peak radiopacity at PLR 4.5 g/ml, with 5.77 mmAl for wMTA[D] and 5.19 mmAl

for wMTA[A]. As PLR decreased, so too did the radiopacity of all the cement systems. At the lowest PLR tested (2.0 g/ml), all cements were still above the required ISO standard. wMTA[A] (at 3.44 mmAl), gMTA[MS] (at 3.33 mmAl) and wMTA[MS] (at 3.45 mmAl) were very close to the limit and gMTA[D] and wMTA[D] less than 1 mmAl from the limit.

The greatest reduction in radiopacity due to reduced PLR was measured for wMTA[D] (-1.96mmAl). Although wMTA[MS] demonstrated the least reduction in radiopacity due to reduced PLR (-1.12mmAl), gMTA[A] was the system that was able to maintain the highest radiopacity at each different level of dilution.

One-way ANOVA analyses were undertaken for cement groups at every PLR tested, and PLR groups for every cement investigated. Tukey's post-hoc test indicated that there were significant differences in radiopacity between cement groups only at the very low (2.0 – 2.5g/ml) and very high (5.0 – 5.5g/ml) PLRs ($p<0.05$). The difference in PLR between groups needed to be at least 2.0g/ml for them to be significantly different ($p<0.05$).

4 DISCUSSION

4.1 Establishment of an experimental MTA-like cement model system

The development of an MTA-like cement model system was key to the systematic analysis of the material, primarily due to the high cost of the commercial MTA (currently £40-50), and to allow for the material to be broken down to its component parts so that modifications of its composition could be undertaken. The original formulation for commercial MTA – ProRoot™ (MS-1098 (00-08B), 2001) – was selected for the cement model system. ProRoot™ was constituted of 75 wt% Portland cement, 20 wt% Bi_2O_3 and 5 wt% gypsum. The recommended PLR of 3.0 g/ml (US5415547, 1994) was used as the baseline mixing ratio in all experiments where PLR was not intentionally modified.

Setting times (of component materials and experimental cement mixes), sample storage duration, POP content and basic PLR differences were all investigated to determine the optimal formulation for the model system.

4.1.1 Setting times of raw materials

To assess the three possible options of Portland cement that could be used in the experimental model system (MC, SC, GPPC), the setting times of these cements, along with the other 'setting' component – POP – were investigated. As expected, POP reached its initial (15 mins) and final (50 mins) set first, prior to the Portland cements. The setting times of the POP were similar to those reported in the literature [Schmidt et al, 1973]; plain POP will always set faster than plain Portland cement, due to the nature of the two different

materials. The premium, more refined, MC and SC cements were quicker to set (initial set 360 mins; final set 510 mins) than the GPPC (initial set 390 mins, final set 600 mins), which made them a more favourable choice for the model system from this experiment.

4.1.2 Setting times of standard PC concentration MTA-like cement

With the initially selected proportions of constituents for the model system (ie. 75 wt% PC, 20 wt% Bi2O3, 5 wt% POP), now our standard, each of the three Portland cements were trialled with the formulation. The initial setting time for the MC-containing cement was significantly faster (70 mins) than the other two cements (120 – 150 mins), though its final setting time was again the same as the SC version. All initial setting times were significantly faster for the model system formulations than the raw Portland cements. This can be explained by two factors: 1. POP is a recognised setting accelerator for Portland cement [O'Beirne et al, 2008]; 2. Bi_2O_3 acts like 'filler' particles in the cement; the presence of 'filler' particles in a cement facilitates its hydration (through the inclusion of bulk to the system) and thus reduces setting time [Rahhal et al, 2012]. It should be noted however, that debate is still currently ongoing as to whether Bi_2O_3 is also chemically involved with the hydration reaction of MTA [Camilleri, 2008] or not [Darvell & Wu, 2011; Li & Coleman, 2015]. Either way, MC Portland cement was found to be the preferable cement to use in the model system based on the parameters investigated .

4.1.3 Setting times of a higher PC concentration MTA-like cement

As MC Portland cement was looking to be the favoured cement to use for the model system, the constituent proportions of the intended primary model system were altered to produce a higher PC concentration MTA-like cement(ie. 85 wt% PC, 10 wt% Bi_2O_3, 5 wt% POP), to test if the cement behaviour for MC detrimentally changed. A higher PC concentration formulation was chosen for testing, as it was ultimately an intention of this research to see if some of the radiopacifier content could be eliminated from the cement system and replaced with more Portland cement (or POP) for a stronger, more robust material.

MC again had the fastest initial (60 mins) and final (480 mins) setting time, closely followed by SC then GPPC. Overall, the higher PC concentration cement set quicker than the standard concentration MTA-like cement and the raw materials, reflecting that although POP and Bi_2O_3 have a positive effect on setting time, a higher Portland cement concentration could significantly improve setting times further.

4.1.4 Effect of POP on setting time

Due to its better setting properties, MC was the Portland cement that was chosen for use in the MTA model system. It also allowed the creation of a grey MTA-like cement, which was comparable with the grey ProRoot™ MTA, that was the dominant commercial product available at the time. The influence of POP on the model system was the next area that required investigation for development; the setting times for the model system with varying POP levels (5 wt%, 10 wt%, 20 wt%, 30 wt%) were recorded. As POP is a recognised setting

accelerator for Portland cement [O'Beirne et al, 2008], it was the cement with the highest POP content (ie. 50 wt% MC, 20 wt% Bi2O3, 30 wt% POP) that had the quickest setting time (5 mins initial set, 30 mins final set), which incrementally decreased as POP content was reduced in samples. It should be noted that although the 30 wt% POP cement was the quickest to set, it was a very stiff paste to mix, and one that most clinicians would consider 'unworkable'. The accepted and recommended PLR for mixing pure POP is 2.0 g/ml [Ferracane, 2001]; as a PLR of 3.0 g/ml was being used for the model system variations, there was insufficient water to react with the highest POP-containing cement (30 wt% POP), producing the dry, stiff mixture that resulted for that composition.

4.1.5 Effect of PLR on setting time

Although the recommended PLR of 3.0 g/ml was chosen for the model system, from the original MTA patent (US5415547, 1994), the model system mixed to various PLRs (2.0 – 5.0 g/ml) was still investigated, to ascertain as to how the cement was affected by the amount of water that was added during its mixing. The primary model system formulation (70 wt% MC, 20 wt% Bi_2O_3, 30 wt% POP) was used, and as expected, the higher the PLR, the quicker the setting time. As with the 30 wt% POP cement from the previous experiment, the 5.0 g/ml cement mixture seemed insufficiently hydrated, resulting in an unworkable, dry and stiff mixture that set very quickly (10 minutes initial set, 50 minutes final set). For decades, it has generally been recognised amongst individuals working with Portland cements that "the water content of a (cement) paste has a marked effect on the time of set as well as upon other properties" (Troxell & Davis, 1938) – all the results for the model system regarding strength, porosity and workability confirmed this (ie. a lower strength indicates a higher porosity and

reduced longevity, with a high porosity especially being detrimental to cement sealing potential.

4.1.6 Setting time experiments overview

As a raw material and incorporated into the model system, MC was the Portland cement that consistently performed the best in the setting time reactions (both initial and final set). SC, the other premium cement, had identical final setting times to MC, however took up to 71% longer to initially set (observed in the 'setting times of standard PC concentration MTA-like cement' experiment). Although MC was the most suitable Portland cement tested to use for the experimental model system, SC was a viable option to consider if a white MTA-like cement model system was needed.

POP is a recognised setting accelerator for Portland cement [O'Beirne et al, 2008] and was found to decrease material setting time incrementally as its concentration was raised. The presence of Bi_2O_3 should also contribute to a decreased setting time, though it is still unclear as to whether the radiopacifier is acting just as a filler, or whether it is also contributing to the initial hydration reaction. PLR is another important factor that influences setting time – as PLR increases, setting time decreases. Both increasing POP content and/or PLR to extremes can lead to a cement mixture that is insufficiently hydrated, that though may set quickly, will be a dry and potentially 'unworkable' paste, which will set and harden to a flawed material.

4.1.7 Effect of sample storage time on material properties of two different MTA-like cements

Upon completion of the setting time experiments and establishment of the primary MTA model system, further investigations were undertaken into sample storage time, POP content and PLR with regard to their effect on material properties.

The first experiment undertaken was comparing both the grey (MC) and white (SC) versions of the primary model system (ie. 75 wt% PC, 20 wt% Bi_2O_3, 5 wt% POP) with regards to sample storage durations prior to compressive strength testing. Due to the high number of samples needed for the experiments throughout the work of this PhD (ie. 7 – 10 per sample group per experiment, plus repeat experiments), the shortest feasible storage time was chosen to allow for the work to be undertaken in a reasonable timeframe. The relationship of POP and PLR to the model system material properties needed to be explored also, in case further alterations to the primary formulation was indicated.

Compressive strength is used by the Portland cement manufacturing industry as a quality indicator for the durability of a cement and thus potential longevity [Committee on Nonconventional Concrete Technologies for Renewal of the Highway Infrastructure (National Research Council), 1997]. Considering the compressive strength results for both the grey (MC-based) and white (SC-based) model systems, both reached a peak strength at 21 days storage, with the grey model system having a stronger set cement (61 MPa), compared to the white version (57 MPa).

Surprisingly, both cements exhibited a loss (of 18 - 23%) in CS at 35 days storage, which was not expected for a Portland cement-based system. See Figure 53 for a typical Portland cement strength progression curve relative to setting/hardening time from the initial set of the cement. The decrease in CS that was observed in both sample groups at 35 days reflected a degradation of the cement system; most likely the dissolution of unreacted residual gypsum (calcium sulphate) and the loss of the soluble alkaline phase (calcium hydroxide), or both.

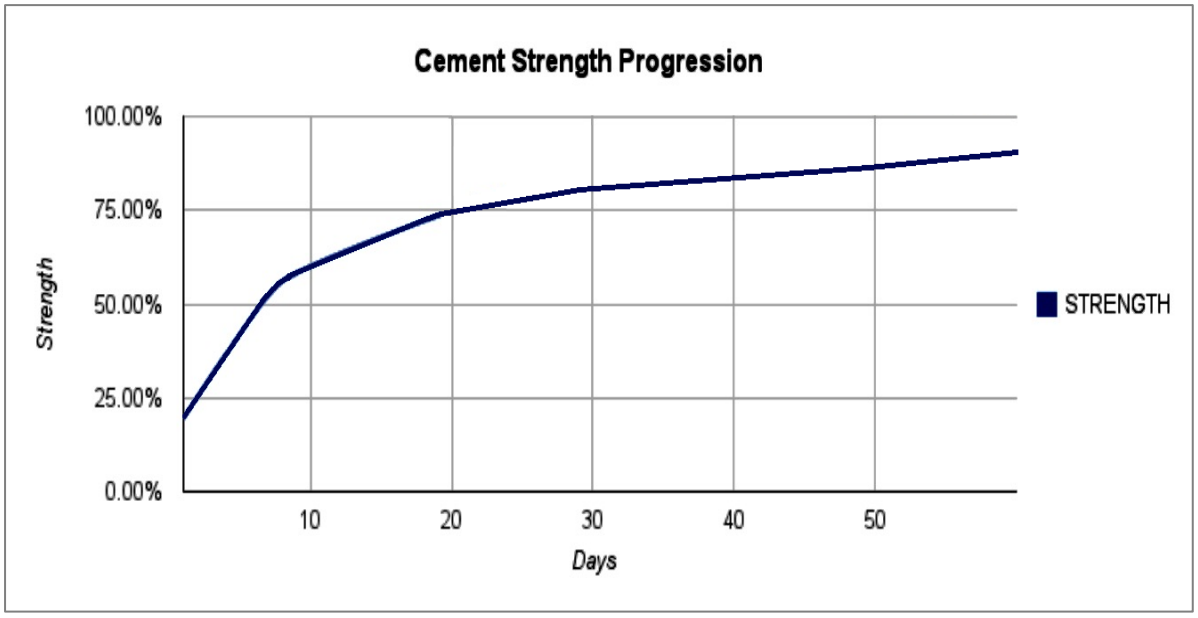

Figure 53: Cement strength relative to the duration of setting/hardening from initial set (t = 0). Cement strength should continue to increase in the presence of moisture as the set cement further hardens over time. Strength should eventually plateau out and not decrease unless some form of degradation occurs [graph adapted from Doubell, 2013]

When looking at the relative porosity figures for the grey and white model systems, the lowest relative porosity was found at 21 days (18%) for the grey model system, and 21 and 35 days (25%) for the white model system. In the grey model system, relative porosity increased again (to 20%) at 35 days, reflecting the degradation of the cement system after the optimal 21 day duration. In the white model system, the fact that relative porosity of the cement remained the same between 21 and 35 days indicated that there was no significant

loss of bulk in the duration, however the cement did degrade in strength (possibly through an alteration in the setting process), evident in the 35 day CS results.

When examining the dry densities and strut densities of both the grey and white model systems over time, the grey cement had near-identical values for both the dry densities (2.06 – 2.08 g/cm^3) and strut densities (2.62 – 2.66 g/cm^3), with only one significant increase in dry density (2.18 g/cm^3) at day 21. As the apparent dry density of a material includes its porosities, whereas the strut density of a material is its true bulk density (excluding voids) the dry density peak at 21 days reflected the grey model system's better material state before a decline by 35 days. Conversely, the white MTA model system had very similar dry densities (1.84 – 1.90 g/cm^3) and strut densities (2.53 – 2.59 g/cm^3), with no significant peak or trough; this indicated that the density and bulk of the material did not change significantly throughout the 35 days of storage investigated (although the CS data indicated that the system was weakened by day 35).

4.1.8 Effect of sample storage time on material properties of a POP-free cement

To investigate the effect of sample storage time on the model cement without the presence of POP addition, an experiment was run to look at the effect of storage time on the material properties of a POP-free cement, as a reference point for the cement system used. Bi_2O_3 content was maintained at 20 wt% and MC content was increased to 80 wt%; sample storage was for 10, 21, 35 and 63 days.

The cement duration with the poorest material properties was 10 days, with the lowest CS (30MPa) and highest relative porosity (25 %) – this was due to the cement still hardening and had ultimately not completed all of its setting reactions by 10 days. This was also reflected when considering the dry density and strut density values for the cement: dry densities (2.14-2.18 g/cm^3) and strut densities (2.59-2.65 g/cm^3) were very close, with only one significant drop in dry density at 10 days storage duration (1.98 g/cm^3), indicating that there was a larger number of voids and flaws in this material at this time. It was also noticed that the inclusion of POP to the model system not only sped up the setting time of the material (ie. POP is a setting accelerator), but increased the CS (by up to 80%), through a modification of the cement chemistry.

The optimal storage duration time was again 21 days, where CS was 49 MPa (20% less than the cement with 5 wt% POP stored for the same period). Relative porosity was at its lowest for this material at 21 days (16%), very close to the relative porosity of the cement with 5 wt% POP stored for the same period. At 35 and 63 days, the CS reduced and relative porosity increased of the POP-free cement, both plateauing out at 43-44 MPa and 18% respectively. In general, the POP-free cement had significantly lower CS values, but similar relative porosity values than the 5 wt%-containing model system. The 'plateauing' effect was only observed in the POP-free cement, as this was the only experiment that stored samples for the 63 day duration; a similar effect would be expected with any other Portland cement used.

4.1.9 Effect of sample storage time on material properties of various POP-containing cements

To further investigate the effect of POP addition to the model system, samples were made with 0 wt%, 5 wt%, 10 wt% and 20 wt% POP and stored for the optimal duration of 21 days. It was the 5wt% cement that had the greatest CS value (61 MPa), followed by the POP-free cement; these two cements had comparably low relative porosities (16-18%), indicating that they had very little unreacted material within. Their apparent dry densities (2.17-2.18 g/cm^3), were higher than those with 10 wt% and 20 wt% POP content (1.91-1.99 g/cm^3), though strut densities were all similar (2.60-2.67 g/cm^3), indicating that the 10 wt% and 20 wt% POP content cements had a greater number of voids/flaws in them (from unreacted material), which explained their lower CS results.

4.1.10 Effect of sample storage time and PLR on material properties of two different MTA-like cements

The last thing assessed in establishing the experimental model system was the effect of storage time and PLR variation on material properties of both the grey and white MTA cements. Both PLRs of 3.0 g/cm^3 and 4.0 g/cm^3 were assessed, though no other PLRs were investigated at this time, as more detailed work was intended on PLRs at a later point (see section 3.5). In the grey model system, it was generally found that PLR 4.0 g/ml had significantly better CS values at 21 and 35 days storage; there was no statistical difference between the CS values of the two PLRs at 10 days, as it appears that the setting/hardening reaction was still ongoing at the time.

Relative porosity was found to be higher in the cement with the lower PLR (as this would mean that the cement had more unreacted water to manage), though this was only statistically significant at 35 days storage duration; at 10 and 21 days, there was no significant difference with the PLRs.

With the white MTA model system, the cement at PLR 4.0 g/ml was significantly stronger than at PLR 3.0 g/ml at 10 and 35 days storage duration; the CS of the two PLRs at 21 days was not statistically different as both cements would have had the opportunity to reach their peak set. Relative porosity figures clearly showed that the white model system had a significantly higher level of porosity at the lower PLR at every storage duration. The relative porosity at 10 days storage was greater than at 21 and 35 days (by 32 – 56%), indicating that the cement had not yet fully set; meaning that the important water-consuming (porosity reducing) reactions within the cement were incomplete.

4.1.11 Storage time, POP content and PLR material properties experiments overview

Out of all the storage times considered/tested for the model system, 7 days generated the weakest cement with a significant level of relative porosity. In the primary model system (ie. 75 wt% MC, 20 wt% Bi_2O_3, 5 wt% POP), apparent dry density and strut dentity for 7 days storage was not statistically different from the other storage days of 10, 21, 35 days, though it was apparent that 21 days produced a slightly improved material from its higher apparent dry density value. From early in these experiments, a storage time of 7 days was ruled out, and further consideration/testing given to the 10, 21 and 35 days.

Considering the grey and white model systems, although both their favoured storage durations were 21 days for optimal material characteristics, this storage duration was too long to be practicable. The 10 day storage duration in the grey cement system produced the second highest compressive strength values out of the four storage durations tested. There was also no significant difference in the relative porosity of the grey model system, between 10 and 35 days, though at 21 days the relative porosity of the system was clearly lower. The apparent dry densities and strut densities were not statistically different across all of the four storage durations either. With all these factors taken into account, it was decided that a 10 day storage duration would be used for the remainder of the research experiments of this PhD, especially since the primary model system to be used was going to be the grey variant. It should be remembered however, that the properties of the cements tested would further improve till around the 21 day mark, and that the white version of the model system (ie. 75 wt% SC, 20 wt% Bi_2O_3, 5 wt% POP) had significantly poorer material properties at 10 days than its grey counterpart.

POP exclusion significantly reduced the material properties of the model system, especially prior to the 21 day optimal storage duration. POP addition to the model system both accelerates setting time and increases the strength and integrity of the cement, providing 5 wt% was not exceeded. PLR also has an effect on the model system around the intended range of 3.0 – 4.0 g/ml, though only affected the grey model system in the 21 and 35 day storage duration; the white version of the model system was more susceptible to PLR alteration, exhibiting changes in properties for each of the storage durations.

In summary, the primary model system of 75 wt% MC, 20 wt% Bi_2O_3 and 5 wt% POP, with PLR of 3.0 g/ml and storage duration 10 days (prior to material testing) was now established for use in the systematic analysis of MTA and future development of the material.

4.2 The use of alternate radiopacifiers in an MTA-like cement

The incorporation of a radiopacifier in an endodontic material, like MTA, is essential due to the need for radiographic assessment following its placement. Please refer to section 3.2 in the Results chapter regarding these experiments. The ISO standard for dental root canal sealing materials (ISO 6876:2001) requires that all root canal sealers have a minimum radiopacity of 3 mmAl equivalent. As commercial MTA contains approximately 20 wt% Bi_2O_3, and it is known that the Bi_2O_3 actually weakens the composition of the cement (Coomaraswamy et al, 2007; Tanomaru-Filho et al, 2012), the model system was tested with radiopacifier levels (x wt% RO) no greater than 20 wt% . POP content of the model system was kept constant at 5 wt%, with the amount of Mastercrete Portland cement (y wt% MC) changing to compensate for the amount of radiopacifier in the system (ie. y wt% MC, x wt% RO, 5 wt% POP).

4.2.1 Effect of radiopacifier content on cement radiopacity

Of all the four radiopacifiers tested (at 0 wt%, 10 wt% and 20 wt% radiopacifier content), only the 20 wt% Bi_2O_3-containing model system (3.71 mmAl) and the commercial ProRoot™ control (3.66 mmAl) – also containing approximately 20 wt% Bi_2O_3 – met the minimum radiopacity standard. All radiopacifiers selected however, had previously been used for medical/dental purposes in the body (Acton, 2013; Sastri, 2014), however at the

concentrations needed for an MTA-like cement, only Bi_2O_3 proved to be satisfactory with regard to the standard. In analysing why $BaSO_4$, Ta_2O_5 and La_2O_3 had lower radiopacity values, the material properties of the radiopacifiers and their cements needed to be considered.

Firstly, each of the pure radiopacifiers used had different specific densities, with Bi_2O_3 having the greatest (8.9 g/cm^3), followed closely by Ta_2O_5 (8.2 g/cm^3), then La_2O_3 (6.5 g/cm^3) and finally $BaSO_4$ (4.5 g/cm^3) with the lowest radiopacifier specific density. The model system without any radiopacifier had a specific density that was even lower than with the radiopacifiers (2.3 g/cm^3). With this in mind, when inspecting the radiopacity results of both10 wt% and 20 wt% radiopacifier addition, the order was the same (highest to lowest density) for both groups, with the most radiopaque cement containing Bi_2O_3, followed by Ta_2O_5, then La_2O_3, $BaSO_4$, and finally the least radiopaque material being the radiopacifier-free cement. The 20 wt% radiopacifier batch was 35-61% more radiopaque compared to the 10 wt% radiopacifier group, with a higher increment in radiopacity (55-61%) observed when doubling the content of the more radiopaque materials (Bi_2O_3 and Ta_2O_5), and a lesser effect (35-42%) recorded when doubling the less dense materials (La_2O_3 and $BaSO_4$).

4.2.2 Effect of radiopacifier content on other cement properties

Although density appears to be the most important factor defining the radiopacity of a cement, there are additional factors (other cement properties) that must be considered to appreciate the cement systems. Radiopacifier addition weakens a cement through the inclusion of inert and/or reactive particles, that will introduce voids/flaws to the cement and possibly affect the cement chemistry, thus potentially altering the cement (Coomaraswamy, 2007; Camilleri, 2008b). In the cases where radiopacifier additives are inert and do not

participate in a cement's hydrolysis reaction, an increased amount of unconsumed water will remain in the cement system, introducing more flaws to the system and further weakening the cement. These effects need to be considered also, as if the cement structure of a system using a high density radiopacifier is compromised by something like a high relative porosity, the highly porous structure of the cement mix can negate the high density of the radiopacifier additive, resulting in an overall weak cement with low radiopacity.

When examining the compressive strength data for the model system with all the radiopacifier variations, it was found that compressive strength was highest in the radiopacifier-free cement system (68MPa) and decreased with the addition of every radiopacifier to varying levels. This supports the understanding that radiopacifier addition compromised the cement material integrity, and thus reduced the strength and potential longevity of the cement. The order of compressive strength performance for the various radiopacifier-containing model systems mirrored the order of radiopacifier density in both the 10 wt% and 20 wt% groups, with comparable figures between the two cohorts. The Bi_2O_3-containing model system was the cement with the highest compressive strength (68 MPa), followed by the cements containing Ta_2O_5 (43-46 MPa), then La_2O_3 (28-32 MPa), and $BaSO_4$ (26-30 MPa). The explanation for the observed trend that 'the denser the radiopacifier additive, the stronger the cement' was obtained from the cement and building industry, where it is well known that high-density aggregates (fillers) in cements produce a more 'solid' and stronger material than low-density aggregates (Iffat, 2015; Ouda, 2015).

Compressive strength is known to have an inverse exponential relationship with relative porosity [Coomaraswamy et al, 2007; Barralet et al, 2003]. As porosity increased for

all additions of radiopacifiers, strength decreased for all compositions. The significantly lower strength of La_2O_3 modified cement when compared with Ta_2O_5 modified cement, despite having very similar porosities at 10 wt% and 20 wt% radiopacifier content, indicated that the mechanism of decreasing strength by introducing flaws might be especially pronounced for La_2O_3.

Relative porosity was higher for all radiopacifier-containing cements than for the radiopacifier-free system. This was likely to arise from the increase in non-water consuming radiopacifier content causing less PC to be able to react with the water. This led to an increased amount of water remaining unconsumed in the Portland cement hydrolysis reaction of the setting cement and subsequently an increased porosity weakening the set structure. The more pronounced difference between the apparent dry density and strut density in the model system with radiopacifiers, compared to without, reflects the effect radiopacifier addition has on the model system.

4.2.3 Radiopacifiers in an MTA-like cement experiment overview

From all the radiopacifiers tested in the model system, Bi_2O_3 was the only one to achieve a satisfactory radiopacity relative to the ISO standard (ISO 6876:2001) at the 20 wt% level, largely due to its high specific density. To compensate for the lower radiopacity of Ta_2O_5, La_2O_3 and $BaSO_4$ an increase in content above 20 wt% would be necessary, however this would likely increase porosity and subsequently decrease strength further.

4.3 The effect of bismuth oxide on MTA

After establishing that Bi_2O_3 was the radiopacifier leading to the highest radiopacity, the effect of Bi_2O_3 content on the cement system was studied further. Please also refer to section 3.3 in the Results chapter regarding these experiments. When investigating the various radiopacifiers that could have been used in the model system, radiopacifier content was limited to no more than 20 wt%. A larger range of 0 – 40 wt% was chosen for this experiment to investigate the effect of Bi_2O_3, to facilitate correlation analyses of the data.

4.3.1 The effect of bismuth oxide on MTA cement properties

The strut density of set Portland cement (around 2.3 g/cm^3) was found to be characteristically lower than the strut density of Portland cement powder (around 3.1 g/cm^3) due to the hydration reaction that occurs when setting (i.e. the consumption and chemical bonding of water, with its low density, to the set cement structure). Thus changes in the degree of hydration of the reactants would cause changes to the PC strut density.

A strong linear correlationship (see Table 4 in Section 3.3) between increase in strut density of the set structure and Bi_2O_3 content increase indicated that density increase was solely due to the addition of denser Bi_2O_3 with its high characteristic density of 8.9 g/cm^3, with the density of the set PC remaining unchanged. It can therefore be concluded that inert Bi_2O_3 did not participate in the setting reaction but also had no effect on the hydration reaction of the Portland cement. As the model system with 20% Bi_2O_3 had the same density "fingerprint" as commercial MTA it can also be concluded that both systems are compositionally similar.

Relative porosity is mainly a measure of the amount of water throughout the cement pore system and can therefore be associated with cement and MTA degradation, i.e. solubility [Fridland & Rosado, 2003], and potential permeability when used as a sealant. Porosity in cement systems can stem from two sources. Firstly from water added to form the cement paste which is not consumed in the setting reaction and secondly from entrapped air in the cement paste due to partially dry powder agglomerates (dry spots) and air bubbles. Non consumed water could explain the strong linear correlationship between relative porosity and Bi_2O_3 content increase: when inert (i.e. not water consuming) Bi_2O_3 content was increased, less PC was present to react with the water, leading to an increase in the amount of unreacted water in the paste as PLR was held constant, thus increasing porosity. As porosity increase is strongly related only to Bi_2O_3 content it can also be concluded that the increase in Bi_2O_3 content did not lead to an increased occurrence of dry spots within the cement paste. The occurrence of the latter might explain the significantly higher relative porosity of commercial MTA compared to the 20 wt% Bi_2O_3 model system (See Table 7).

Table 7: Wet compressive strength, relative porosity, apparent dry density and strut density of cement samples with increasing Bi2O3 content. Either the standard deviation or minimum error of method are given for mean values.

Bi_2O_3 Content (wt%)	Compressive Strength (MPa)	Relative Porosity (%)	Apparent/Dry Density (g/cm3)	Strut/Bulk Density (g/cm3)
0	82.1 ± 11.2	15 ± 1	2.02 ± 0.02	2.38 ± 0.02
10	40.0 ± 11.4	17 ± 1	2.08 ± 0.02	2.50 ± 0.02
20	36.2 ± 7.6	23 ± 1	2.12 ± 0.02	2.76 ± 0.02
30	31.1 ± 5.2	28 ± 1	2.14 ± 0.02	2.96 ± 0.02
40	28.7 ± 4.5	31 ± 1	2.23 ± 0.02	3.22 ± 0.02
20 (Grey ProRoot™)	33.0 ± 1.0	31 ± 1	1.89 ± 0.02	2.74 ± 0.02

Commercial MTA is known to have poor handling and low ease of mixing (Chng et al, 2005; Kogan et al, 2006). This might lead to the increased air enclosure in dry spots within the cement paste increasing porosity. The Portland cement for the model system in this study was choosen on the basis of ease of mixing and handling thus reducing air enclosure.

Compressive strength is used by the Portland cement manufacturing industry as a quality indicator for the cement´s durability and hence potential longevity [Committee on Nonconventional Concrete Technologies for Renewal of the Highway Infrastructure (National Research Council), 1997]. Takahashi et al. (1997) proposed and proved a relationship between compressive strength and relative porosity for Portland cement based systems. A relationship which was later proven to be valid for other calcium phosphate cement-based systems [Barralet et al, 2002, 2003]:

$$CS = \sqrt{\frac{E_0 \cdot R}{\pi \cdot c}} \cdot e^{-const \cdot RP} \qquad \text{Eq. 1}$$

(CS: compressive strength; E_0: modulus of zero porosity material; R: fracture surface energy; c: critical flaw size; RP: relative porosity)

If the materials constants (under the square root) remain unchanged, equation 1 simplifies to a linear relationship between the natural logarithm (ln) of compressive strength and relative porosity:

$$\ln(CS) = \text{constant} \cdot RP \qquad \text{Eq. 2}$$

The natural logarithm of measured compressive strengths over measured relative porosities for the model system is shown in Figure 54.

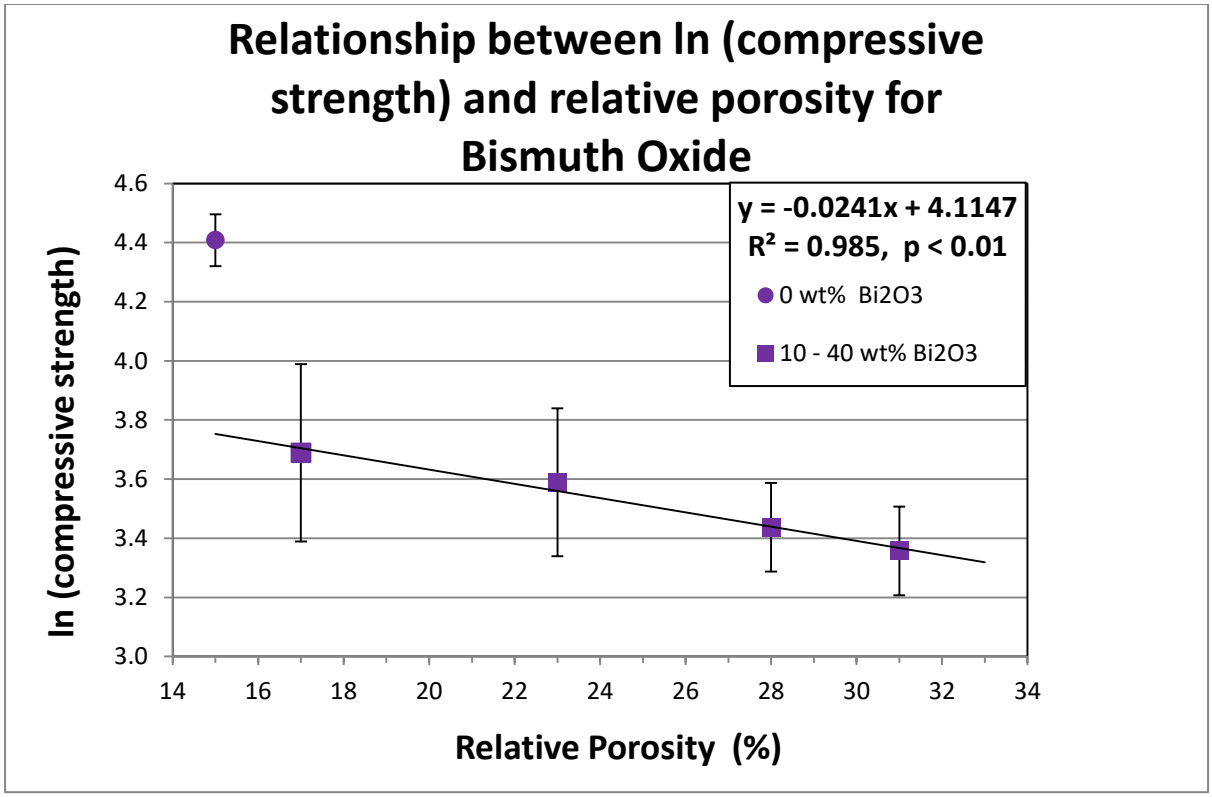

Figure 54: Linear relationship between ln(compressive strength) and relative porosity for Bi_2O_3 contents of cement mixture of 10 wt%, 20 wt%, 30 wt% and 40 wt%. The significantly higher value for 0wt% Bi_2O_3 content illustrates the strength-deteriorating effect of radiopacifier addition

The strict linear relationship (R^2 = 0.99, p<0.01) of equation 2 is fullfilled once Bi_2O_3 is included in the system, strength then decreases with increasing porosity. From this it can be concluded that the material constants remain the same for the cement with varying Bi_2O_3

content. Compressive strength for the cement not containing any Bi_2O_3 was, however, significantly higher and departed from the strong linear correlationship. The strength deterioration by more than a factor of 2 when Bi_2O_3 content increased from 0 to 10 wt%, associated with a porosity increase of only 2 %, could only be explained by a change in material constants, presumably critical flaw size, by a factor of 4 (square root) caused by the incorporation of inert and not chemically bonded Bi_2O_3 into the set cement.

4.3.2 The effect of bismusth oxide on MTA experiment overview

The addition and increase of Bi_2O_3 radiopacifier content resulted in a deterioration of mechanical strength and an increase in relative porosity of the MTA-like cement system. Strong linear correlationships exist between Bi_2O_3 content and relative porosity, dry density and strut density the cement model system. Relative porosity in the cement stems from two sources: 1. Water - unconsumed by the hydrolysis setting reaction of the cement; 2. Air - entrapped within the cement mixture or as powder agglomerates not penetrated by water. Bi_2O_3 addition was also found to alter material constants, such as critical flaw size, which then remained constant with further radiopacifier increase, compromising the material integrity and longevity of the cement. The primary model system (ie. 75 wt% MC, 20 wt% Bi_2O_3, 5 wt% POP) was found to be comparable in composition and strength to commercial grey ProRoot™ cement, though had a lower porosity due to the improved workability of the Portland cement component. This validation of the model system opened up the possibility for its use by other researchers in the development of MTA and like-cements.

4.4 The effect of PLR on the workability of an MTA-like cement

After establishing a better understanding of the component parts of MTA (through the primary model system), and its behaviour as a whole, the preparation of the cement and handling by clinicians was the next thing to be investigated. Please also refer to section 3.4 in the Results chapter regarding these experiments. In clinical practice, the majority of clinicians and nurses who mix MTA do so imprecisely and 'by eye'. To investigate mixing and workability, a single-blinded study was developed in which experienced specialist dental clinicians provided their subjective opinion on material consistency and handling properties. The primary model system was used for this study, now that it had been shown to have comparable material properties to the grey ProRoot™ MTA [Coomaraswamy et al, 2007].

4.4.1 The effect of PLR on the consistency and handling of an MTA-like cement

The strut density should be a constant characteristic for a Portland cement-based material independent of PLR when the degree of hydration of the cement reactants is the same [Coomaraswamy et al, 2007]. See Figure 55. All the strut densities of the set material between PLRs of 3.0 to 5.0 g/ml were not significantly different, which suggested that raising the PLR within that range did not affect the degree of conversion of the reactants after 10 days of setting.

Increasing PLR of any cement system is known to theoretically lead to a less porous and thereby denser material as less residual water is left throughout the structure [Fridland & Rosado, 2003; Hofmann et al., 2006]. Relative porosity changes have been proven to be in an inverse relationship with the compressive strength of Portland cement [Coomaraswamy et al., 2007; Takahashi et al. 1997] and porosity also directly correlates to the solubility of the material [Fridland & Rosado 2003]. As long as not done beyond the requirements of the cement chemistry, increasing PLR should not only decrease solubility potential, but also increase mechanical stability; both aspects improving the prognosis with regard to the durability of a cement in a moist or wet environment.

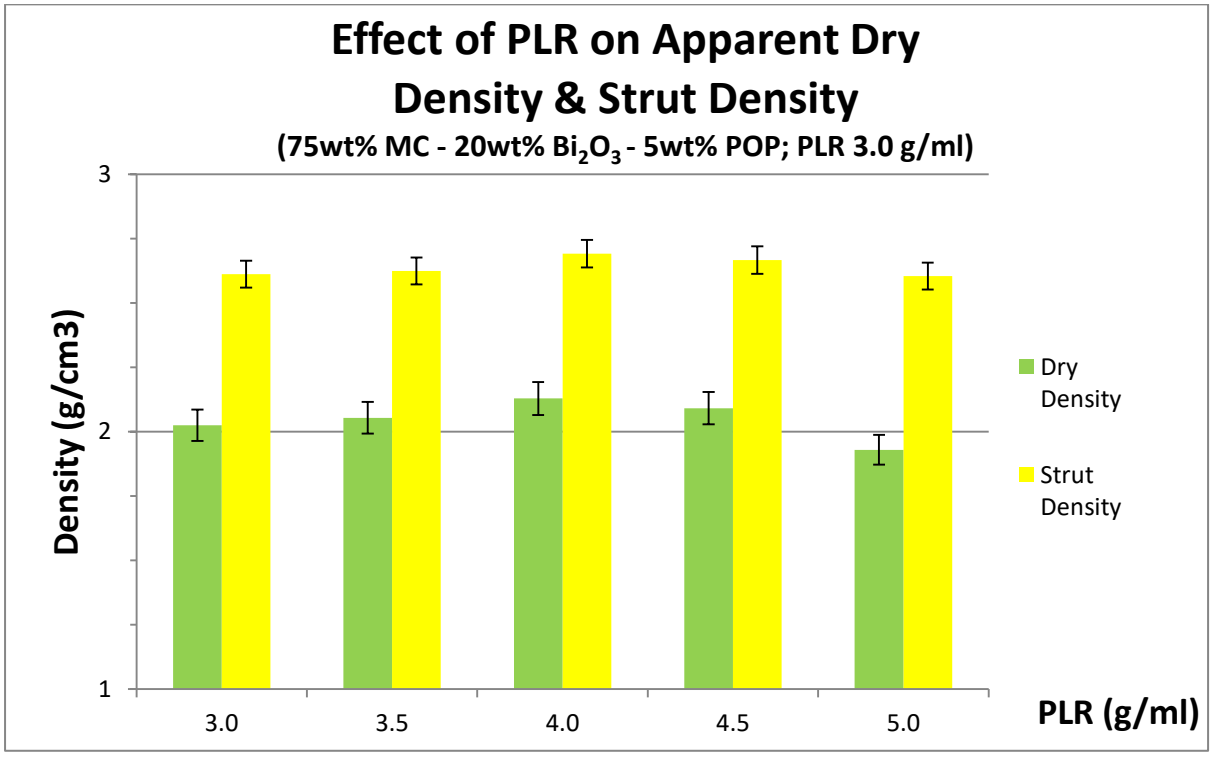

Figure 55: The relationship of PLR to apparent dry density and strut density in the primary model system.

The results demonstrated that trend, when increasing PLR from 3.0 to 4.0 g/ml: porosity decreased, compressive strength and density increased (See Table XX, Section 3.4).

However, when increasing PLR further to 4.5 and 5.0 g/ml, porosity increased and density decreased, leading to a significant deterioration in strength at 5.0 g/ml. In this case it is likely that at such a high PLR the cement paste did not contain enough water to wet the surface of all powder particles, thus creating a cement paste and therefore increasing the amount of air in dry spots of the paste were enclosed air leads to increased porosity, decreased density and therefore deteriorated mechanical strength of the set structure.

The 5 assessors were not significantly different for consistency and handling in their overall assessment, however, the large deviations (seen in the whiskers) of Figures 43 and 44 (Section 3.4) suggest, that there is a wide range in perception with regard to rating those characteristics.

At PLR of 3.0 – 3.5 g/ml, the cement consistency was generally rated as being too soft/runny, with the same range (1-4) and median (2) of perceived scores. At these PLRs too much water was present in the paste leading to the visible generation of a water layer on the paste, specifically a partial phase separation of liquid and solid phase. Conversely, at high PLRs of 5.0 and 5.5 g/ml there were insufficient amounts of water to create a cement paste; perceived scores were more focused in range (4-5) and assessors more certain of their opinion that the paste mix was too dry. PLRs of 4.0 and 4.5 g/ml were perceived as being almost ideal, and also coincided with the optimal cement mechanical properties (i.e. highest mechanical strength, strut and apparent dry densities, and the lowest porosity).

Handling was rated low for low PLRs of 3.0 to 3.5 g/ml and high PLRs of 5.0 and 5.5 g/ml. This could be explained by the fact that a dry or too liquid paste was considered difficult to manipulate and place clinically. A paste too liquid is especially problematic as MTA-like systems are usually placed in moist environments leading to further dilution of the paste. The highest handling ratings were achieved for PLRs of 4.0 to 4.5 g/ml, coinciding with the PLRs where consistency was rated highest and where material properties were best.

4.4.2 The effect of PLR on the workability of an MTA-like cement experimental overview

The results in this study suggested that Portland cement-based systems in endodontic applications should be used within their ideal PLR range to achieve the best level of workability of the paste and the set material properties. Cement pastes mixed at levels too low (≤ 3 g/ml) or high (≥ 5 g/ml) are perceived as 'unworkable' through the addition of too little or too much water, and the resultant material is weaker and flawed.

The experimental findings also indicated that Portland cement-based systems are almost intuitive for experienced clinicians with regard to gauging the near-optimal PLR necessary for the best cement mix. Despite the MTA manufacturers providing precise mixing ratios for the preparation of their cements, it appears that the 'mix by eye' approach taken by many experienced clinicians and nurses (who use MTA on a regular basis) is an acceptable technique to use, as it still generally yields a cement mix that is very close to the desired PLR and best cement material properties.

4.5 The effect of dilution on MTA

4.5.1 The effect of dilution on both the radiopacity and material characteristics of MTA

The current commercial MTA cement systems consists of Portland cement with a bismuth oxide radiopacifier, each cement has its own individual constitution and characteristics. At the recommended PLR of 3.0 g/ml, gMTA[A] was found to have the highest radiopacity of all the cements tested (4.62mmAl); as this was true for every level of PLR tested and could be explained through examining the MTA cement specific material densities recorded. The specific material density is unique to each cement and reflects its basic constituent parts [Richerson et al, 2006]. gMTA[A] also had the highest specific material density (2.75g/cm^3), signifying that it was the most dense of all the MTA cements tested; this indicated a higher content of the high-density bismuth oxide compared with all the other MTAs, due to fewer flaws taking up space in the material.

Of the commercial cements, wMTA[A] had the lowest level of radiopacity at PLR 3.0g/ml (4.22mmAl), though this could not be explained by the cement's comparatively moderate specific material density, and thus it was evident that another factor was influencing its radiopacity. It was only when the cement relative porosities were considered that wMTA[A] was found to be the most porous cement (34%), explaining its inferior level of radiopacity. Conversely, wMTA[D] had the lowest relative porosity of the cements tested (16%) , and despite comparatively low specific material density (Bi_2O_3 content), had a level of radiopacity somewhere in the middle.

DISCUSSION

When each of the cements' results are plotted, an inverted parabolic curve relationship is evident between radiopacity and PLR, with its vertex indicating the PLR for optimal radiopacity. gMTA[D] had a peak radiopacity (5.17mmAl) at PLR 5.5g/ml, followed by gMTA[A] (6.25mmAl), gMTA[MS] (4.98mmAl) and wMTA[MS] (4.57mmAl) at 5.0g/ml. The commercial white MTA cements tested reached their optimal radiopacity at PLR 4.5g/ml, and reached higher levels of radiopacity than the gMTA[D] and both versions of the model system. The observed peak radiopacity difference of gMTA[D] at PLR 5.5g/ml and gMTA[A], with the lower PLR of 5.0g/ml and yet higher peak radiopacity, reflects that gMTA[A] requires a slightly lesser amount of water for its complete setting reaction to occur, and is the cement that was able to maintain the highest levels of radiopacity , due to its high Bi_2O_3 density.

On comparison of cement radiopacity at greatest dilution vs peak PLR level, wMTA[D] was the system most detrimentally affected by liquid addition (-1.96mmAl) and gMTA[D] the least (-1.22mmAl). Although at PLR 3.0 g/ml, wMTA[D] was the least porous cement when compared to the other systems, its extreme shift in radiopacity over the PLR levels tested reflect that this cement was most susceptible to dilution; the opposite was found for gMTA[D]. It is both the specific density of the cement powder and the cement system's characteristic response to water addition that contribute to the outcome and properties of the set cement.

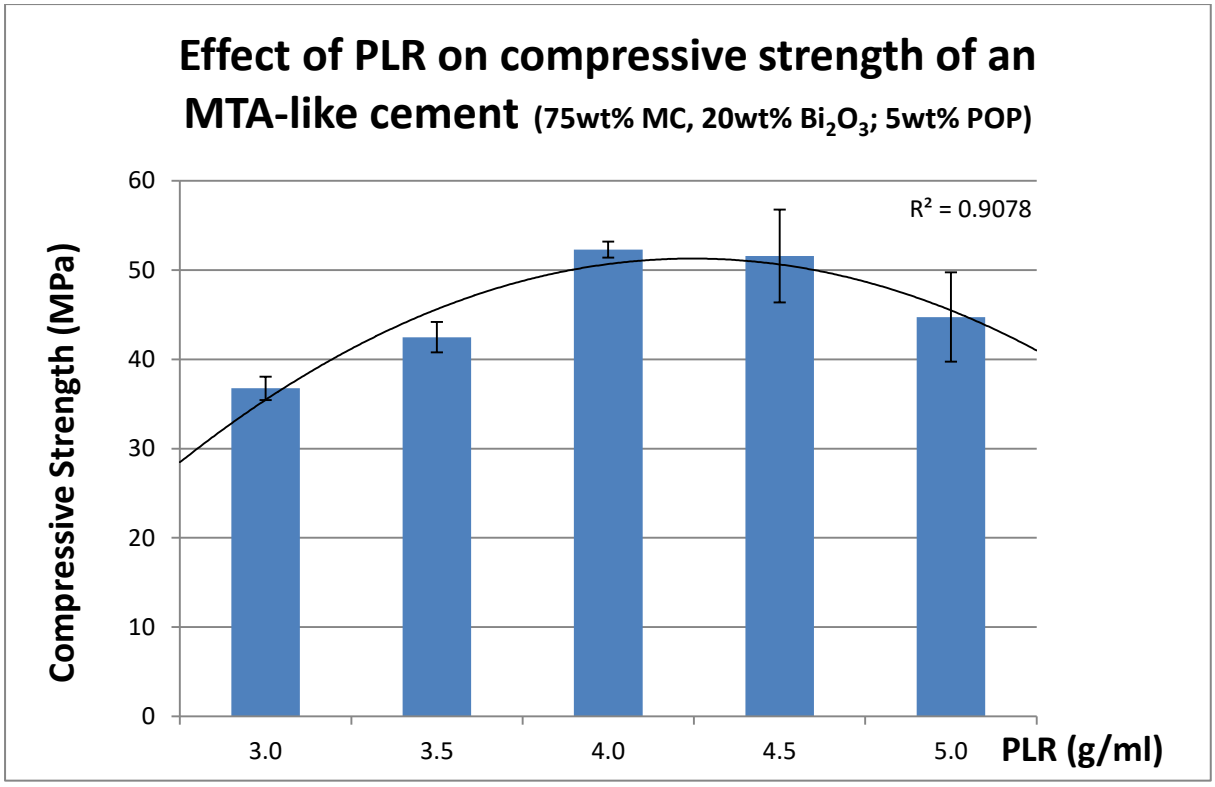

Figure 56: The effect of PLR on the compressive strength of an MTA-like cement. A trendline has been drawn in with good fit. Peak compressive strength was found to be at 4.0 g/ml, with a deterioration of this characteristic at lower and higher PLRs.

Figures 56 and 57 demonstrate that the compressive strength increases and relative porosity of an MTA cement decreases with PLR, to a maximum level, and then the reverse occurs again at higher PLRs. At low PLR, an excess of unreacted water remains in the cement, resulting in increased porosity and reduced radiopacity. At high PLR, there is insufficient water to react with the cement, resulting in air trapped in powder agglomerates thus increasing the material porosity and subsequently reducing its radiopacity.

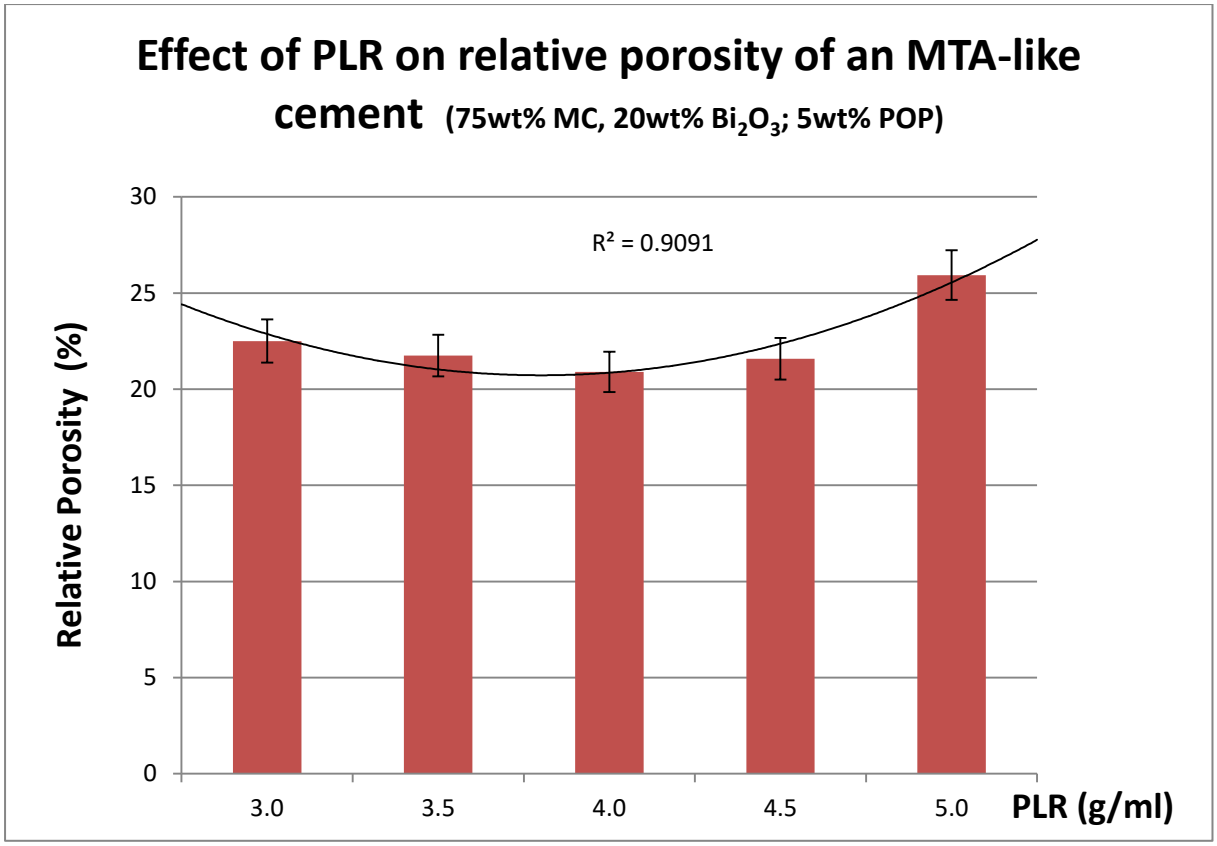

Figure 57: The effect of PLR on the relative porosity of an MTA-like cement. A trendline has been drawn in with good fit. The lowest relative porosity was found to be at 4.0 g/ml, with an increase of porosity at lower and higher PLRs.

4.5.2 The effect of dilution on MTA experimental overview

Every MTA cement system tested, though they appeared quite similar in composition (see Figure 58, where strut densities are not significantly different from each other), produced set cements with their own unique material properties profile. Although a cement may contain the same dense radiopacifier, its handling, hydration and setting characteristics will influence the density of the final set cement, which will in turn affect levels of radiopacity. Peak PLRs for the radiopacity of the cements tested ranged between 3.5 – 4.5 g/ml which is higher than the recommended 3.0 g/ml manufacturer recommended mixing ratio. The PLR for the optimal compressive strength and relative porosity fell right in the middle of that range, 4.0 g/ml.

DISCUSSION

The dilution of any MTA cement with water/fluid reduces its radiopacity often significantly; for some samples, very close to the standard requirement of 3 mmAl. MTA should therefore be mixed at a higher PLR (ideally 4.0 – 4.5 g/ml), especially when being placed into a moist operating field (eg. apicectomies, apexifications, perforation repairs), to avoid clinically significant reduction of radiopacity in the bulk, or locally at the tissue-cement interface.

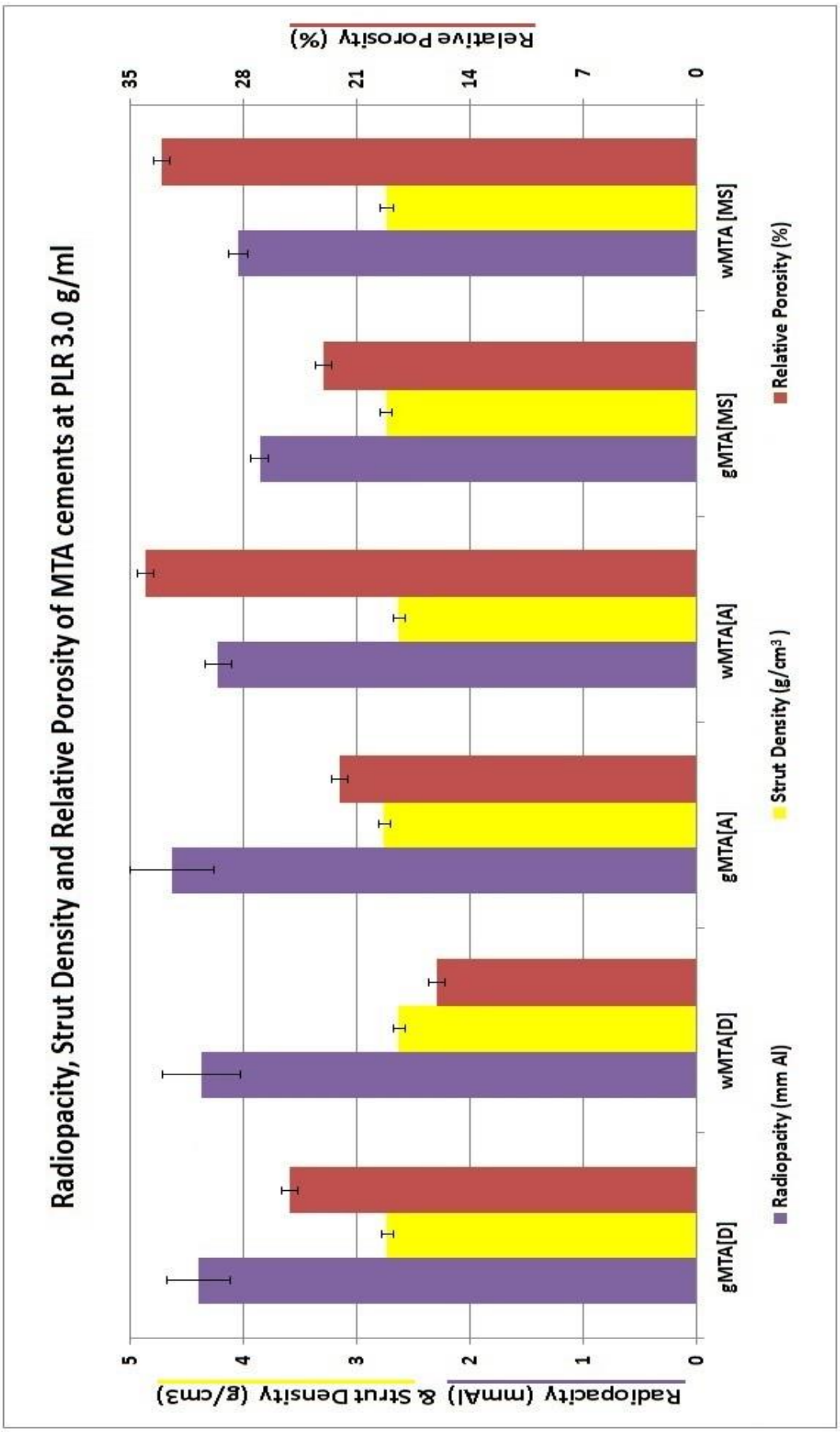

Figure 58: The relationship between radiopacity, strut density and relative porosity in the primary model system at PLR 3.0 g/ml

CONCLUSIONS

The cost-prohibitive and unmodifiable factors of commercial MTA pose a barrier for researchers to further investigate and develop the material. This research led to the development of an MTA-like cement model system, that has been shown not only to have similar properties and composition to one of the commercial products, ProRoot™ MTA (by Dentsply) [Coomaraswamy, 2007], but has now been used by researchers in the development of enhanced MTA [Murphy et al, 2007; O'Beirne et al, 2008] and bone cement systems (Wynn-Jones et al, 2012).

Of the raw Portland cements assessed for the model system, Blue Circle Mastercrete was the material that had both the optimal setting time and material properties necessary. Combined in the proportions of 75 wt% MC, 20 wt% Bi2O3, 5 wt% POP, this made up the primary model system that formed the basis of all MTA-like cement testing throughout the subsequent research undertaken. Blue Circle Snowcrete had material properties slightly inferior to MC, though better than the General Purpose Portland Cement assessed – this made SC a satisfactory component for a white MTA-like cement model system (75 wt% MC, 20 wt% Bi2O3, 5 wt% POP) when needed.

When the storage time for samples prior to material testing was assessed, it was found that cement set/hardening was complete around the 21-day mark, and thus material properties were in their optimal state at this time. For the MC-containing primary model system, the 10-day sample storage duration provided the second best cement, over the 7- and 35-day storage periods. As the 10-day storage time was a more practicable time to use for the large number

of samples that needed to be made/tested for this research, it was chosen as the standard duration to be used for all subsequent experiments from that point, with the understanding that the material properties for any MTA-like cement tested were further going to improve to around 21 days, prior to 'plateauing' out or declining to a degree due to the dilution of unreacted cement component(s) during storage.

Calcium sulphate (eg. POP) content in MTA was found to have a significant bearing on the material properties of the cement system. Setting time, strength, porosity and density were all influenced by POP addition, with the optimal POP concentration being 5 wt%, relative to the cement material properties assessed. As POP content was raised above 5 wt%, setting times reduced, though porosity increased, resulting in a weaker cement with poorer integrity. Although a cement without POP had a slightly lower (statistically insignificant) difference in relative porosity to a cement containing 5 wt%, the POP-containing cement had improved compressive strength (statistically significant difference) and general long-term prognosis.

The clinically necessary addition of a radiopacifier to an MTA-like PC-based system significantly reduced mechanical stability and increased porosity for all investigated radiopacifiers. Bi_2O_3 was the best radiopacifier overall as it provided the highest strength and lowest porosity and also the highest radiopacity of all modified cements. Ta_2O_5 was a close second to Bi_2O_3, though was unable to reach the minimum radiopacity standard (3mmAl) at the desired 20 wt% concentration. Both the specific densities of the radiopacifiers and their effect on the MTA-like cement system played a significant part in the outcome radiopacity of the cement produced. The model system with 20wt% Bi_2O_3 addition also showed a nearly

identical radiopacity and strut density compared with commercial MTA but had higher strength and lower porosity. Although a lower proportion of radiopacifier in an MTA-like cement would improve the material properties of the system, 20 wt% appears to be the minimum amount of Bi_2O_3 radiopacifier needed to meet the minimum radiopacity standard expected; the other radiopacifiers tested would be needed in greater concentrations again, due to the lower radiopacity they produce in a cement.

Pure Portland cement has been proposed as an alternative to MTA [Abdullah et al, 2002; Camilleri et al, 2006], however it lacks radiopacity for the radiographic follow-up assessment after an endodontic procedure [Danesh, et al, 2006]. This research demonstrated that the addition of Bi_2O_3 radiopacifier to a Portland cement changes the material constants of the cement dramatically by acting as flaws within the cement matrix.

The addition of Bi_2O_3 radiopacifier decreased mechanical stability by introducing flaws and increased porosity by leaving more unreacted water within the Portland-cement based (MTA-like) endodontic model system. Flaws in the set cement matrix might exacerbate existing cracks (which inevitably exist due to the stress of initial setting in a Portland cement based system); and increased porosity is known to increase the solubility and thus the degradation of the material. This might potentially affect the longevity of the material, compared to pure Portland cement, as the set material is more likely to degrade and hence more likely to be compromised as a sealant.

CONCLUSIONS

With regards to the preparation and workability of an MTA-like cement, the use of an optimum PLR when mixing the paste is crucial for improving the consistency, handling and set material properties. For the primary model system used, consistency and handling were rated at near-ideal at the PLRs where the cement showed highest mechanical strength and density, and the lowest porosity: around 4.0 – 4.5 g/ml. As the model system used in this research has been proven to be very similar to grey ProRoot™ MTA, this recommended higher PLR for improved material properties should be applicable to at least this one commercial MTA, if not them all. The conclusions drawn from the 'effect of PLR on the workability of an MTA-like cement' experiments were reinforced by the findings of the 'effect of dilution on MTA' experiments. The dilution of any MTA cement with water/fluid reduces its radiopacity often significantly; for some samples very close to the standard requirement. It is thus advisable that MTA-like cements are mixed at higher PLRs (ideally 4.0-4.5g/ml), especially when being placed into a moist operating field, to ensure sufficient radiopacity of the material is achieved, both in the bulk and locally at the tissue-cement interface.

MTA has been used in modern day dentistry for over two decades now, and has proven its worth through its multiple applications and high treatment success rates if administered correctly. Although not an ideal material in many respects, MTA does have several properties that give it the advantage as both a therapeutic agent and endodontic restorative material. More research is needed into the cement and the development of related-products, which hopefully now will be facilitated through the use of the model system described in this research.

FURTHER WORK

As this PhD research was undertaken part-time over several years, a lot of the further work intended for the model system had been done by full-time students in our school, by the time this thesis was finally submitted. The MTA model developed from this work has now been used for numerous undergraduate/postgraduate research projects, including PhDs in both the dental and medical field [O'Beirne, 2010; Wynn-Jones, 2013], and towards the development of an MTA-like cement product for commercial release.

Further to the investigations undertaken in this project, additional work has been done using the model cement system on the effect of calcium sulphates on MTA [O'Beirne, 2010], the use of setting accelerators to improve the properties of MTA [Murphy, 2008], the development of an MTA-like system for orthopaedic applications [Wynn-Jones, 2013; US20140060390, 2014] and the effect of pH on MTA setting and properties (currently unpublished research).

All of the work undertaken in this PhD has been relating to the physicochemical properties of MTA, thus additional research could be done regarding the cement on the cellular and biological level. As it was found that a PLR of 4.0-4.5 g.ml provided the optimal material properties and radiopacity, investigating the biological effect of MTA mixed at various PLRs would provide a more complete understanding of whether an increase in PLR from the manufacturer's recommended 3.0 g/ml would have any significant biological implications.

FURTHER WORK

It has been found that freshly mixed Portland cement is acutely toxic to cells in contact with the material, leading to cellular necrosis [Wynn-Jones, 2013]. Further research exploring the effect of newly mixed MTA on biological models could lead to modifications of the cement to hopefully reduce the impact of this initial negative outcome.

The radiopacifier investigations undertaken in this PhD involved four different compounds, though was not an exhaustive list of the possible materials that could be used for this purpose. Although Bi_2O_3 was found to be the best radiopacifier for MTA from the four additives tested, it has now been found to be associated with post-operative dental discolouration [Marciano et al, 2015; Voveraityte, 2016]. Further work could be carried out to additionally explore radiopacifier possibilities, their relationship to the MTA-like cement when incorporated into the system, and if an alternative radiopacifier existed without the associated discolouration problems.

Fluoride at low concentrations has been found to have a therapeutic effect on dental pulp cells [Thaweboon, 2003]. Preliminary work with the model system and fluoride additives has shown a favourable effect on material properties. This is another area for investigation in the future, where limited scientific research has been done; it would be interesting to see if the therapeutic potential for an MTA-like cement could be further enhanced in any way.

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APPENDIX 1

Additional Experimental Data

ESTABLISHING AN EXPERIMENTAL MTA-LIKE MODEL SYSTEM

Plain materials (PLR 3.0 g/ml)		
Cement	Initial setting time (mins)	Final setting time (mins)
POP	15	50
GPPC	390	600
Mastercrete	360	510
Snowcrete	360	510

75PC-20Bi_2O_3-5POP (PLR 3.0 g/ml)		
Cement	Initial setting time (mins)	Final setting time (mins)
MS with GPPC	150	570
MS with Mastercrete	70	510
MS with Snowcrete	120	510

85PC-10 Bi_2O_3-5POP (PLR 3.0 g/ml)		
Cement	Initial setting time (mins)	Final setting time (mins)
MS with GPPC	80	570
MS with Mastercrete	60	480
MS with Snowcrete	80	480

Varying POP content ([Bi_2O_3] kept constant)		
Cement	Initial setting time (mins)	Final setting time (mins)
75MC-20Bi_2O_3-5POP	70	510
70MC-20Bi_2O_3-10POP	30	240
60MC-20Bi_2O_3-20POP	15	40
50MC-20Bi_2O_3-30POP	5	30

75MC-20BO-5POP (varying PLR)		
PLR	Initial setting time (mins)	Final setting time (mins)
2.0	720	1260
3.0	70	510
4.0	40	270
5.0	10	50

75MC-20BO-5POP (PLR 3.0) Time stored in H2O (days)	Compressive Strength (MPa)	Relative Porosity (%)	Dry Density (g/cm3)	Strut Density (g/cm3)
7	40.01 ± 8.10	22 ± 1	2.08 ± 0.02	2.66 ± 0.02
10	53.66 ± 3.50	21 ± 1	2.08 ± 0.02	2.64 ± 0.02
21	61.30 ± 5.43	18 ± 1	2.18 ± 0.02	2.64 ± 0.02
35	46.75 ± 11.99	20 ± 1	2.06 ± 0.02	2.62 ± 0.02

Either the standard deviation or minimum error of method are given for mean values

75PC-20BO-5POP (PLR 3.0)		Compressive Strength (MPa)	Relative Porosity (%)	Dry Density (g/cm3)	Strut Density (g/cm3)
Portland Cement	Time stored in H2O (days)				
MC	10	53.66 ± 3.50	21 ± 1	2.08 ± 0.02	2.64 ± 0.02
MC	21	61.30 ± 5.43	18 ± 1	2.18 ± 0.02	2.64 ± 0.02
MC	35	46.75 ± 11.99	20 ± 1	2.06 ± 0.02	2.57 ± 0.02
SC	10	34.48 ± 8.94	33 ± 1	1.84 ± 0.02	2.59 ± 0.02
SC	21	57.48 ± 13.98	25 ± 1	1.90 ± 0.02	2.55 ± 0.02
SC	35	47.16 ± 4.04	25 ± 1	1.89 ± 0.02	2.53 ± 0.02

Either the standard deviation or minimum error of method are given for mean values

80MC-20BO-0POP (PLR 3.0) Time stored in H2O (days)	Compressive Strength (MPa)	Relative Porosity (%)	Dry Density (g/cm3)	Strut Density (g/cm3)
10	29.61 ± 3.16	25 ± 1	1.98 ± 0.02	2.65 ± 0.02
21	49.42 ± 14.90	16 ± 1	2.17 ± 0.02	2.59 ± 0.02
35	43.99 ± 1.59	18 ± 1	2.14 ± 0.02	2.59 ± 0.02
63	42.86 ± 10.94	18 ± 1	2.18 ± 0.02	2.64 ± 0.02

Either the standard deviation or minimum error of method are given for mean values

yMC-20BO-xPOP (PLR 3.0; 21 days storage) POP wt% (x)	Compressive Strength (MPa)	Relative Porosity (%)	Dry Density (g/cm3)	Strut Density (g/cm3)
20	24.95 ± 4.40	28.43 ± 1	1.91 ± 0.02	2.67 ± 0.02
10	33.48 ± 3.09	25.63 ± 1	1.99 ± 0.02	2.67 ± 0.02
5	61.30 ± 5.43	17.52 ± 1	2.18 ± 0.02	2.64 ± 0.02
0	49.42 ± 14.90	16.31 ± 1	2.17 ± 0.02	2.60 ± 0.02

Either the standard deviation or minimum error of method are given for mean values

75MC-20BO-5POP		Compressive Strength (MPa)	Relative Porosity (%)	Dry Density (g/cm3)	Strut Density (g/cm3)
PLR	Time stored in H2O (days)				
3.0	10	53.66 ± 3.50	21 ± 1	2.08 ± 0.02	2.64 ± 0.02
3.0	21	61.30 ± 5.43	18 ± 1	2.18 ± 0.02	2.64 ± 0.02
3.0	35	46.75 ± 11.99	20 ± 1	2.06 ± 0.02	2.57 ± 0.02
4.0	10	52.31 + 2.45	20 ± 1	2.08 ± 0.02	2.62 ± 0.02
4.0	21	77.07 + 8.21	17 ± 1	2.22 ± 0.02	2.68 ± 0.02
4.0	35	65.96 + 17.18	17 ± 1	2.17 ± 0.02	2.62 ± 0.02

Either the standard deviation or minimum error of method are given for mean values

75SC-20BO-5POP		Compressive Strength (MPa)	Relative Porosity (%)	Dry Density (g/cm3)	Strut Density (g/cm3)
PLR	Time stored in H2O (days)				
3.0	10	34.48 ± 8.94	33 ± 1	1.84 ± 0.02	2.73 ± 0.02
3.0	21	57.48 ± 13.98	25 ± 1	1.90 ± 0.02	2.55 ± 0.02
3.0	35	47.16 ± 4.04	25 ± 1	1.89 ± 0.02	2.53 ± 0.02
4.0	10	49.23 ± 7.68	25 ± 1	1.98 ± 0.02	2.63 ± 0.02
4.0	21	53.14 ± 14.70	16 ± 1	2.05 ± 0.02	2.45 ± 0.02
4.0	35	53.37 ± 5.25	16 ± 1	2.03 ± 0.02	2.41 ± 0.02

Either the standard deviation or minimum error of method are given for mean values

EVALUATION OF DIFFERENT RADIOPACIFIERS FOR AN MTA-LIKE CEMENT

Radiopacifier	mm Al
0 wt% Bi2O3	0.83
10 wt% Bi2O3	2.40
20 wt% Bi2O3	3.71
Grey ProRoot	3.66

Radiopacifier	mm Al
0 wt% BaSO4	0.83
10 wt% BaSO4	1.10
20 wt% BaSO4	1.48
Grey ProRoot	3.66

Radiopacifier	mm Al
0 wt% Ta2O5	0.83
10 wt% Ta2O5	1.73
20 wt% Ta2O5	2.78
Grey ProRoot	3.66

Radiopacifier	mm Al
0 wt% La2O3	0.83
10 wt% La2O3	1.30
20 wt% La2O3	1.85
Grey ProRoot	3.66

10% Radiopacifier Sample	Compressive Strength (MPa)	Relative Porosity (%)	Dry Density (g/cm3)	Strut Density (g/cm3)
95MC-0RO-5POP	67.92 ± 16.91	15.88 ± 1	1.96 ± 0.02	2.33 ± 0.02
10 wt% Bi_2O_3	46.38 ± 3.89	19.87 ± 1	1.97 ± 0.02	2.46 ± 0.02
10 wt% La_2O_3	31.82 ± 7.95	21.22 ± 1	1.83 ± 0.02	2.44 ± 0.02
10 wt% Ta_2O_5	45.63 ± 2.19	19.84 ± 1	1.97 ± 0.02	2.45 ± 0.02
10 wt% $BaSO_4$	30.02 ± 4.86	25.48 ± 1	1.80 ± 0.02	2.42 ± 0.02
Grey ProRoot	34.38 ± 14.79	27.41 ± 1	1.90 ± 0.02	2.62 ± 0.02
20% Radiopacifier Sample	**Compressive Strength (MPa)**	**Relative Porosity (%)**	**Dry Density (g/cm3)**	**Strut Density (g/cm3)**
95MC-0RO-5POP	67.92 ± 16.91	16 ± 1	1.96 ± 0.02	2.33 ± 0.02
20 wt% Bi2O3	43.77 ± 10.15	22 ± 1	1.98 ± 0.02	2.55 ± 0.02
20 wt% La2O3	28.19 ± 2.01	24 ± 1	1.85 ± 0.02	2.44 ± 0.02
20 wt% Ta2O5	43.12 ± 4.41	24 ± 1	1.98 ± 0.02	2.61 ± 0.02
20 wt% BaSO4	25.90 ± 4.83	26 ± 1	1.81 ± 0.02	2.43 ± 0.02
Grey ProRoot	34.38 ± 14.79	27.41 ± 1	1.90 ± 0.02	2.62 ± 0.02

Either the standard deviation or minimum error of method are given for mean values

Radiopacifier	10wt% (mmAl)	20wt% (mmAl)
BaSo4	1.10 ± 0.03	1.48 ± 0.03
La2O3	1.30 ± 0.03	1.85 ± 0.06
Ta2O5	1.73 ± 0.05	2.78 ± 0.04
Bi2O3	2.40 ± 0.06	3.71 ± 0.03
Grey ProRoot	3.66 ± 0.07	
None	0.83 ± 0.06	

THE EFFECT OF BISMUTH OXIDE ON AN MTA-LIKE CEMENT

Bi2O3 Content (wt%)	Compressive Strength (MPa)	Relative Porosity (%)	Apparent/Dry Density (g/cm3)	Strut/Bulk Density (g/cm3)
0	82.1 ± 11.2	15 ± 1	2.02 ± 0.02	2.38 ± 0.02
10	40.0 ± 11.4	17 ± 1	2.08 ± 0.02	2.50 ± 0.02
20	36.2 ± 7.6	23 ± 1	2.12 ± 0.02	2.76 ± 0.02
30	31.1 ± 5.2	28 ± 1	2.14 ± 0.02	2.96 ± 0.02
40	28.7 ± 4.5	31 ± 1	2.23 ± 0.02	3.22 ± 0.02
20 (Grey ProRoot)	33.0 ± 1.0	31 ± 1	1.89 ± 0.02	2.74 ± 0.02

Either the standard deviation or minimum error of method are given for mean values

THE EFFECT OF PLR ON WORKABILITY OF AN MTA-LIKE CEMENT

75MC-20BO-5POP PLR	Compressive Strength (MPa)	Relative Porosity (%)	Dry Density (g/cm3)	Strut Density (g/cm3)
3.0	36.76 ± 3.44	22.50 ± 1	2.02 ± 0.02	2.61 ± 0.02
3.5	42.49 ± 4.62	21.75 ± 1	2.05 ± 0.02	2.62 ± 0.02
4.0	52.31 ± 2.45	20.90 ± 1	2.13 ± 0.02	2.69 ± 0.02
4.5	51.59 ± 13.72	21.58 ± 1	2.09 ± 0.02	2.67 ± 0.02
5.0	44.74 ± 13.33	25.93 ± 1	1.93 ± 0.02	2.60 ± 0.02

Either the standard deviation or minimum error of method are given for mean values

THE EFFECT OF DILUTION ON MTA

MTA Cement	Radiopacity (mm Al)	Strut Density (g/cm3)	RP (%)
gMTA[D]	**4.39 ± 0.28**	**2.74 ± 0.02**	**31 ± 1**
wMTA[D]	**4.36 ± 0.41**	**2.62 ± 0.02**	**16 ± 1**
gMTA[A]	**4.62 ± 0.53**	**2.75 ± 0.02**	**22 ± 1**
wMTA[A]	**4.22 ± 0.12**	**2.62 ± 0.02**	**34 ± 1**
gMTA[MS]	**3.85 ± 0.08**	**2.67 ± 0.02**	**28 ± 1**
wMTA [MS]	**4.04 ± 0.08**	**2.73 ± 0.02**	**33 ± 1**

Either the standard deviation or minimum error of method are given for mean values

APPENDIX II

Publications

APPENDIX III

Conference Presentations

Conference Presentations:

University of Birmingham Graduate School Research and Enterprise Gala, (2010)
Birmingham (UK); ***poster presentation***
"Effect of Cement Paste Dilution on the Radiopacity of MTA".

British Society of Paediatric Dentistry Annual Scientific Conference, (2009)
Birmingham (UK); ***poster presentation***
"Use of Mineral Trioxide Aggregate in the Management of Complicated Crown Fractures".

"Bioceramics 20 [20th International Symposium of Ceramics in Medicine], (2007)
Nantes (France); ***poster presentation***
"Evaluation of Different Radiopacifiers for an MTA-like Dental Cement".

"Bioceramics 20 [20th International Symposium of Ceramics in Medicine], (2007)
Nantes (France); ***oral presentation (presented by collaborator)***
"Monitoring the Accelerated Setting of Portland Cement Based Dental Materials".

Pan-European Federation of the International Association for Dental Research Meeting
Dublin (UK); ***oral presentation*** (2006)
"Effect of Radio-Opacifier Content on an MTA-like Root Filling Material".

Pan-European Federation of the International Association for Dental Research Meeting
Dublin (UK); ***poster presentation (presented by collaborator)*** (2006)
"Workability and Mechanical Performance of an MTA-like Root Filling Cement".