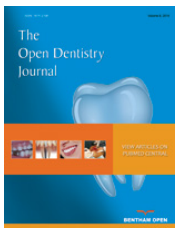

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REVIEW ARTICLE

Portland Cement: An Overview as a Root Repair Material: Applications and Various Modifications

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Abstract:

Background:

Portland cement has promisingly been utilized for the reconstruction of root perforation and bone defects, although its key drawbacks, including low mechanical properties and radiopacity as well as long setting time, necessitate pragmatic modifications.

Objective:

The main objective of this review was an overview of portland cement as a root repair material, its applications and various modifications.

Methods:

The electronic search of the literature was done on the Pubmed and Google Scholar databases with the keywords of Portland cement, carbon nanotube, graphene oxide, MTA, pulp capping, and root repair material.

Results:

The first part of this paper presents the data published in the literature on applications of Portland cement in endodontic situations, including vital pulp therapy, root perforation repair, root canal filling and root-end filling following apical endodontic surgery. This bioactive endodontic cement has shown promising success rates compared to mineral trioxide aggregate (MTA), however, considerable modifications are required in order to improve its clinical performance and expand its application scope as a root repair material. Hence, nano-reinforcements (graphene oxide, carbon nanotube, silica and hydroxyapatite) and extensive chemical modifications incorporated into Portland cement composition to produce innovative bio-dental materials with superior rheological properties have been discussed. Moreover, the current knowledge of the microstructure, mechanical properties and durability of nanomaterial-incorporated cement has been summarized. Ultimately, this article outlines the main points of animal and clinical studies on resin-modified Portland cement (TheraCal) as a pulp capping material and suggests further investigations prior to marketing authorization.

Conclusion:

It can be concluded that Portland cement has the potential to be used as an acceptable pulp capping material with the least complaints in the long term.

Keywords: Portland cement, Carbon nanotube, Graphene oxide, MTA, Pulp capping, Root repair material.

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1. INTRODUCTION

Portland cement is extensively used worldwide as concrete for construction works and as a bioactive endodontic cement in dentistry. It consists of tri and dicalcium silicates, tricalcium aluminate, and tetracalcium alumino ferrite and calcium sulfate as gypsum [1, 2]. The introduction of bioactive cement is a significant breakthrough in the production of dental and bone cement for the reconstruction of root perforations or bone defects. Application of Portland cement in endodontics for vital pulp therapy or as an apical barrier in necrotic teeth has shown successful results compared to MTA and previously used

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materials such as amalgam, calcium hydroxide and glass ionomer [1, 2]. The first part of this review includes *In vitro* and *in vivo* studies conducted on Portland cement as a pulp capping material thus far.

Various Portland cement-based materials are available, although the drawbacks, including long-lasting setting time, low mechanical properties (compressive, tensile and flexural strength), poor resistance to microcracks and not acceptable radiopacity limit their application scope. According to the national standards, the initial setting time of Portland cement is about 1 h, and the final setting time is about 6.5 h [3]. With tremendous scientific effort, improvements have been made in the multi-functional properties of cementitious materials and their durability without compromising the biological properties [4]. Structural reinforcements and rheological modifications can be achieved by modifying cement with the optimum percentage of nanoscale materials such as metal mineral admixtures, metal oxides or carbon-based materials [5]. Several reports expressed a positive view on the inclusion of nanoparticles of alumina, titanium dioxide, nono-silica, graphene and graphene oxide, as well as carbon nanotubes and nanofibers in Portland cement to improve the microstructural behavior, increase the compressive strength and alter its setting time [6 - 9]. Nano-reinforcements act as a filler, which grants the cement a dense structure and hinders the initiation and propagation of microcracks when used in load-bearing areas [5]. Of note, the radiopacity of Portland cement is not enough to be visualized radiographically, therefore, radiopacifying agents are typically included in it. Bismuth oxide containing Portland cement has improved radiopacity and has been used under the name of MTA, although recent concerns such as cytotoxicity or tooth color alteration enforce using alternative materials, including zirconium oxide, niobium oxide and silver nanoparticles as radiopacifiers [10]. The modified Portland cement by radiopacifiers must meet certain requirements in order to be allowed to enter clinical testing.

Given that there is no comprehensive review of Portland cement and its applications, this paper includes Portland cement publications in the dental field and a cursory glance over material studies from peer-reviewed journals published in English and discusses miscellaneous modifications incorporated into cement's structure to improve its characteristics, microstructure and to facilitate its preparation and handling for dental procedures.

2. METHODS

The data search was completed using the Pubmed and Google Scholar databases with the keywords of Portland cement, carbon nanotube, graphene oxide, MTA, pulp capping, root repair material.

3. RESULTS

- The collected data showed that Portland cement has been applied in endodontic situations, including vital pulp therapy, root perforation repair, root canal filling and root-end filling following apical endodontic surgery with promising success rates compared to mineral trioxide aggregate (MTA).
- Modifications (nano-reinforcements and/or chemical modifications) are essential in order to improve the clinical performance of Portland cement.
- Some animal and clinical studies on resin-modified Portland cement (TheraCal) as a pulp capping material suggest further investigations prior to marketing authorization.

4. DISSCUSSION

4.1. Portland Cement Applications in Endodontics

4.1.1. Repair of Perforations

4.1.1.1. Animal Studies

Application of Portland cement to repair intraradicular perforations in dog premolar teeth showed acceptable sealing capacity due to the mineralized tissue formation, periradicular tissue regeneration and scarce inflammatory response in the perforated area [11]. Repairing perforation with calcium sulfate barrier and white, type II or type IV Portland cement as an obturation material also resulted in high remineralization, and no difference was found between various materials in terms of newly formed bone [12, 13].

4.1.1.2. Clinical Studies

In a case report using Portland cement for sealing furcation perforation, Burges *et al*. reported no complaints after 9 years [14].

4.1.2. Root-end Filling

4.1.2.1. Clinical Studies

In a pilot study, Silva SR *et al*. compared MTA and Portland cement as root-end filling materials after endodontic surgery of maxillary and mandibular anterior teeth. Similar bone formation was obtained in both groups and periradicular regeneration occurred in all cases after six months [15].

4.1.3. Resorption

In a case report, Burges *et al*. found promising long-term results following the application of Portland cement for the treatment of a tooth with internal resorption and wide granulation tissue [14].

4.1.4. Pulp Capping

4.1.4.1. Animal Studies

Histological analysis of pulp tissues six months after the application of white and gray Portland cement and white and gray MTA for pulp capping of dog premolars showed no acute inflammation and the materials were equally effective in vascularization and fibrous tissue formation [16]. Reparative hard tissue formation following the application of Portland cement as a pulp capping material in baboon's premolar teeth was reported to be similar in thickness and quality to the MTA group, whereas significantly less and more incomplete hard

tissue was detectable in the calcium hydroxide group [2]. The newly formed hard tissue seemed to be atubular and contained porosities and defects and bore no resemblance to secondary dentin in all groups evaluated.

In contrast, Shayegan *et al*. observed the formation of a complete thick layer of hard tissue 3 weeks after pulp capping of primary pig teeth with Portland cement, MTA, β-tricalcium phosphate and calcium hydroxide. Although some specimens in the calcium hydroxide group showed incomplete dentin bridge formation, given the normal pulp reaction, intact odontoblastic layer and absence of inflammatory response and bacteria, this study indicated the biocompatibility and regenerative ability of mentioned endodontic cement [17].

4.1.4.2. Clinical Studies

Short-term histological analysis of the effect of Portland cement as a pulp capping material on human third molars showed an inflammatory response in most cases, and Dentin Bridge was detected in only 10% of teeth. Twenty-one days after treatment, odontoblast-like cells were presented below the pulp tissue [18].

4.1.5. Pulpotomy

4.1.5.1. Animal Studies

Histological analysis of the dog's pulp tissue following pulpotomy using MTA and white and gray Portland cement showed that all materials were equally effective in preserving pulp vitality. After 4 months of follow-up, normal pulp tissue without inflammation or infection was observed [19, 20]. Another study by Holland *et al*. corroborated these results in a 60-day follow-up [21]. Comparison of Portland cement, MTA, β-TCP, ferric sulfate and formocresol effectiveness for pulpotomy in an animal study on pigs resulted in normal pulp tissue response in Portland cement, MTA and β-TCP groups, while acute inflammatory cells, internal resorption and necrotic areas were detected in ferric sulfate and formocresol groups [22].

4.1.5.2. Clinical Studies

Clinical studies on human primary teeth showed that Portland cement and MTA might serve as effective pulp capping materials [23, 24]. These materials yielded a success rate of 100% in 24-month follow-up clinically and radiographically, whereas the application of calcium hydroxide resulted in internal resorption and frequent necrotic areas [24]. Mineralized material deposition and the beneath healthy pulp tissue were detectable during the 6-month follow-up of teeth treated with Portland cement. Another 24-month follow-up study by Yildirim *et al*. reported 93.3% and 86.7% clinical and radiographic success rates in primary teeth treated with Portland cement for pulpotomy. Although no significant difference was between the Portland cement and MTA groups, internal resorption, periodontal space widening and furcation radiolucency were observed in the Portland cement group [25]. These results are in agreement with a study by Vilimek *et al*. [26]. In a similarly designed study, Sakai *et al*. found a success rate of 100% in teeth treated with Portland cement and MTA during 24-month follow-up. Notwithstanding, during the first 6 months, mineralized material deposition was detected in 100% and 57% of teeth treated with Portland cement and MTA, respectively [23]. Twelve-month follow-up of primary molars following conventional pulpotomy using Portland cement showed satisfactory results in preserving pulp vitality [27, 28]. The long-term success of human primary teeth pulpotomy using Portland cement and formocresol was also evaluated, and 100% of the success rate was achieved by Portland cement [29]. Pulpotomy treatment of human premolar teeth with Portland cement and MTA also showed no significant difference in the inflammatory response, soft tissue organization and dentin bridge formation [30].

Furthermore, the application of radiopaque Portland cement (containing zirconium oxide or iodoform) for pulpotomy of primary teeth showed no adverse effects in terms of clinical, radiographic or histological outcomes [31, 32].

4.1.6. Portland Cement as an Apical Barrier for Nonvital open Apex Teeth

In a case series study, Chakraborty *et al*. reported successful clinical outcomes after 6-month follow-up of 3 cases with nonvital and open apex conditions following the application of white Portland cement as an apical barrier [33]. Using white Portland cement apical plug with an absorbable collagen sponge barrier for apexification, De-Deus *et al*. reported clinical success and no signs of periapical rarefaction in a one-year follow-up [34].

4.1.7. Indirect Pulp Treatment

4.1.7.1. Clinical Studies

Application of Portland cement, MTA and calcium hydroxide for indirect pulp treatment showed a 90.3% success rate regardless of the used material. In 6-month follow-up, both Portland cement and MTA were found effective in limiting the infection and treatment of deep carious lesions [35].

4.1.8. Portland Cement as an Intracanal Medicament

4.1.8.1. In-vitro Studies

The intracanal application of calcium silicate-based cement (white Portland cement, white ProRoot MTA and Biodentine) with chlorhexidine as a vehicle showed higher calcium ion release compared to calcium hydroxide during the 14 days period. The addition of 2% chlorhexidine extended the setting time up to 84 days and consequently facilitated the removal of medicament [36].

4.1.9. Treatment of Hypersensitivity

Treatment of dentin hypersensitivity using a calcium silicate paste based on Portland cement occluded dentinal tubules by the formation of a fine crystalline layer and demonstrated the ability of this material to reduce dentin permeability. SEM/EDX analyses revealed the precipitate deposits and formation of a calcium-reach layer on the dentin surface, suggesting the clinical use of Portland cement as a desensitizing agent [37].

4.1.10. Portland Cement in Bone Tissue Engineering

Calcium silicate-based materials are a potential candidate for bone tissue engineering due to their good physical properties, biocompatibility and acceptable bioactivity and osteoconductivity [38]. Portland cement stimulates the expression of bone remodeling markers and the growth of bone tissue with the formation of osteoid and new trabeculla [39, 40]. The behavior of osteoblast lineage cultured on Portland cement has been previously discussed. Three-dimensional porous Portland cement-based scaffolds with high mechanical strength compatible with that of normal bone have been proposed. These scaffolds support human osteoblast cell adhesion and proliferation [41, 42]. Portland cement scaffold modified with polydimethylsiloxane enhanced cell metabolism and alkaline phosphatase activity after 2 weeks [42].

Portland cement is well-suited for bone repairing in load-bearing areas such as vertebrae or mandible. In order to produce injectable bone cement using Portland cement with accelerated setting time, studies introduced liquefying additives into it [43]. Modification of Portland cement with 2 wt% sodium or potassium citrate improved its injectability and reduced the setting time while increasing the compressive strength [44]. It is worth mentioning that at low concentrations, citrate acts as a Portland cement retardant by slowing down the dissolution of alite and aluminate, although, in high concentrations, it accelerates the hydration process [45, 46]. Other additives, such as calcium chloride and calcium nitrate, are also used for modifying Portland cement injectability whilst maintaining its compressive strength [47].

Coating $CaCO_3$ on cement by carbonation is a feasible way to enhance the biocompatibility and bioactivity of Portland cement. Exposure of carbonated Portland cement to calcium phosphate solution resulted in the precipitation of apatite-like crystals (carbonated apatite), which strongly resemble natural bone structure [48].

Polymethyl methacrylate bone cement containing hydrated and anhydrous white Portland cement as a filler also showed satisfying apatite formation ability. The formed apatite layer was denser, and pH value was higher in hydrated Portland cement [49].

5. WHITE PORTLAND CEMENT

Although various characteristics of white Portland cement have been extensively discussed previously, a brief review of the composition of this material would be worthwhile. The grayish color of Portland cement led to the introduction of modified Portland cement named white Portland cement to match the tooth color. The color change from gray to white is due to significantly fewer chromospheres, predominantly iron, manganese, chromium and titanium in white brands [50]. White and gray Portland cement and white and gray MTA are composed of the same major components [51]. White Portland cement is made of high-grade limestone with less than 0.15 wt% Fe_2O_3 and 0.015 wt% MnO and white clay and other products with less than 1 wt% FeO and 0.8 wt% TiO_2 [52]. A comparison of type I white and gray Portland cement showed that white cement has more dicalcium silicate and aluminate and trace of tetracalcium aluminoferrite [50]. SEM analysis of white Portland cement showed various amorphous, globular and crystalline particles dispersed over ground with finer particles [53].

6. MODIFICATION OF PORTLAND CEMENT WITH RADIOPACIFIERS

Portland cement is slightly radiopaque (0.86-2.02 mm Al) in the natural state; thus, it does not meet the International Organization for Standardization (ISO 6876) requirements. Literature has introduced various radiopacifiers, including zinc oxide, zirconium oxide, titanium dioxide, barium sulfate, iodoform, bismuth oxide, calcium tungstate and ytterbium trifluoride to allow the distinction of Portland cement from adjacent dentin and anatomical structures, although it is uncertain if favorable properties would be satisfied (Table **1**) [54, 55]. Thus far, Portland cement/lead oxide and Portland cement/bismuth oxide have shown the highest radiopacity values, while Portland cement/zinc oxide showed the lowest values of radiopacity. Nevertheless, all of them exhibited higher radiopacity values than dentin, and therefore they can be potentially added to Portland cement as radiopacifier agents [56]. It has been reported that all materials containing Portland cement and radiopacifiers promote pH values similar to pure Portland cement and release calcium ions gradually [55, 57].

Table 1. Studies on the addition of various radiopacifiers to Portland cement.

Refs.	Study Type	Type of PC	Radiopacifier	Other Groups	Obtained Results
Bortoluzzi *et al*. [181]	Animal study	WPC	20% Bi_2O_3	MTA + 20% $BaSO_4$ MTA + 20% Bi_2O_3 MTA ProRoot	Modified PC showed a higher inflammatory response with no necrosis area during 60 days of implantation, no difference was between groups in reparative tissue
Li *et al*. [65]	*In vitro*	WPC	20% Bi_2O_3 20% ZrO_2	White PC	Bi_2O_3 extended initial and final setting times and retarded the hydration degree ZrO_2 did not affect the setting time and accelerated the hydration degree
Sabari *et al*. [90]	Animal study	WPC	20% Bi_2O_3 20% ZrO_2 20% Iodoform	MTA	Similar tissue reactions were observed among all groups during 60 days
Souza *et al*. [87]	*In vitro*	PC	2%, 5%, 10%, 15% $(BiO)_2CO_3$	MTA Angelus	$(BiO)_2CO_3$ increased the setting time, all groups had similar solubility, PC+15% $(BiO)_2CO_3$ showed radiopacity similar to MTA, acceptable biological properties in all groups were observed

(Table 1) contd.....

Refs.	Study Type	Type of PC	Radiopacifier	Other Groups	Obtained Results
Mestieri *et al.* [182]	*In vitro*	WPC	Nb_2O_5 µP Nb_2O_5 nP	MTA	Similar or higher cytocompatibility and bioactivity compared to MTA were observed
Flores *et al.* [183]	*In vitro*	WPC+10,20,30% wallostonite WPC+10,20,30% BG	20% Bi_2O_3	MTA Angelus	Addition of wollastonite and BG reduced the setting time and radiopacity, acceptable solubility and physical properties were observed compared to MTA
Vazquez *et al.* [184]	*In vitro*	PC	30% ZrO_2 AgNPs	WMTA WMTA + AgNPs	Addition of AgNPs favored the physicochemical and mechanical properties and increased the antibacterial activity
Guerreiro *et al.* [142]	*In vitro*	PC+ 10, 20% nHA	30% ZrO_2	WMTA	Addition of nHA improved the antibacterial activity and setting time but harmed the mechanical properties and solubility
Slompo *et al.* [185]	*In vitro*	WPC	20% ZrO_2	WMTA	Low cytotoxicity was observed
Antonijevic *et al.* [81]	*In vitro*	PC	30% YbF_3	CSC+30% YbF_3+40%$CaCO_3$ CSC+30% YbF_3+35% nHA	PC+ YbF_3 had the most radiopacity, setting time and fluoride release with acceptable biocompatibility and micromechanical properties
Bosso *et al.* [55]	*In vitro*	Type II PC(CSC) Resinous CSC	ZrO_2 nP ZrO_2 µP Bi_2O_3 Nb_2O_5 $CaWO_4$	WMTA	CSC+ ZrO_2 µP, Nb_2O_5 and $CaWO_4$ had similar results to WMTA with shorter setting time
Tanomaru *et al.* [83]	*In vitro*	PC + 10%, 20% CaO	30% ZrO_2 30% Nb_2O_5	WMTA	PC+ZrO_2+ 20%CaO had a setting time similar to WMTA but with lesser compressive strength
Mestieri *et al.* [85]	*In vitro*	PC	30% Nb_2O_5 nP 30% Nb_2O_5 µP	WMTA	MTA had more radiopacity, but OPC had greater cell viability
Guerreiro *et al.* [76]	*In vitro*	PC PC+5%ZnO PC+10%ZnO	ZrO_2	-	Addition of ZnO decreased the compressive strength, all materials had similar antibacterial activity
Marciano *et al.* [186]	*In vitro*	PC	20% ZrO_2 20% $CaWO_4$	WMTA	Bovine teeth filled with all materials showed color alteration after 60 days
Viapiana *et al.* [82]	*In vitro*	PC+ epoxy resin	ZrO_2 nP, µP Nb_2O_5 nP, µP	AH Plus MTA Fillapex	OPC showed radiopacity similar to MTA and had the highest Ca release and crystalline deposition
Tanomaru *et al.* [10]	*In vitro*	WPC	ZrO_2 nP, µP Nb_2O_5 nP, µP	WMTA	MTA had the most radiopacity, all materials had antibacterial activity
Chen *et al.* [97]	*In vitro*	PC	Bi_2O_3+0, 15, 30, 100% YSZ	-	PC+ Bi_2O_3+ 15%YSZ had the most radiopacity but similar cell viability to PC+ Bi_2O_3
Viapiana *et al.* [187]	*In vitro*	PC+ epoxy-based vehicle	ZrO_2 nP, µP Nb_2O_5 nP, µP	AH Plus	All sealers had great sealing ability, favorable overall characteristics were observed compared to AH Plus
Antonijevic *et al.* [67]	*In vitro*	PC	10, 20, 30% ZrO_2 10, 20, 30% Bi_2O_3 10, 20, 30% YbF_3	ProRoot MTA	Bi_2O_3 decreased the compressive strength of PC but ZrO_2 and YbF_3 increased it, Bi_2O_3 extended the setting time but ZrO_2 and YbF_3 did not affect it
Viapiana *et al.* [86]	*In vitro*	PC	ZrO_2 nP, µP Nb_2O_5 nP, µP	AH Plus MTA Fillapex MTA Sealapex	PC+ ZrO_2 µP and PC+ Nb_2O_5 nP had setting time similar to Fillapex, AH Plus had the most compressive strength, OPC had acceptable solubility but the least radiopacity
Weckwerth *et al.* [71]	*In vitro*	WPC	Bi_2O_3 $(BiO)_2CO_3$ $Bi_5H_9N_4O_{22}$ ZrO_2	-	Addition of $(BiO)_2CO_3$ and $Bi_5H_9N_4O_{22}$ increased the solubility, no antibacterial activity but acceptable antifungal activity was observed
Coleman *et al.* [188]	*In vitro*	WPC	ZrO_2	-	ZrO_2 reduced the initial and final setting time of PC and had a slight effect on hydration behavior
Guerreiro *et al.* [57]	*In vitro*	PC	ZrO_2 Bi_2O_3 $CaWO_4$	ZOE	All OPC compositions had great antibacterial activity
Duarte *et al.* [66]	*In vitro*	WPC	ZrO_2 Bi_2O_3 $CaWO_4$	WMTA	WMTA had the least setting time, all radiopacifiers increased PC's setting time, all materials had alkaline pH and released Ca

(Table 1) contd.....

Refs.	Study Type	Type of PC	Radiopacifier	Other Groups	Obtained Results
Formosa *et al*. [73]	*In vitro*	PC	20% Bi_2O_3	TCS TCS+20% Bi_2O_3	Bi_2O_3 increased the setting time, OPC had acceptable compressive strength when cured in distilled water
Cutajar *et al*. [78]	*In vitro*	PC	0-50% ZrO_2	ProRoot MTA	Addition of 30% ZrO_2 showed great physicochemical and mechanical properties
Cornelio *et al*. [92]	*In vitro*	PC	ZrO_2 Bi_2O_3 $CaWO_4$	ZOE	High biocompatibility was observed
Camilleri *et al*. [91]	*In vitro*	PC	$BaSO_4$ Au Ag/Sn alloy	MTA Intermediate restorative material	OPC had extended setting time compared to PC, but similar compressive strength was observed PC+Au had setting time and compressive strength similar to MTA
Vivan *et al*. [72]	*In vitro*	PC clinker	$CaSO_4$ Bi_2O_3	MTA Angelus MTA Bio Sealepox Light-cured MTA	Radiopacity of all materials was acceptable except for light-cured MTA
Min *et al*. [98]	*In vitro*	PC	Bi_2O_3	Pure PC	No difference was observed in the mineralization of hDPCs in PC and OPC groups
Bortoluzzi *et al*. [189]	*In vitro*	WPC	Bi_2O_3 $BaSO_4$ Iodoform	Pure PC WMTA	All materials had acceptable radiopacity except for PC and PC+ $BaSO_4$
Duarte *et al*. [56]	*In vitro*	PC	$(BiO)_2CO_3$, Bi_2O_3 $Bi_5H_9N_4O_{22}$ $BaSO_4$, ZnO, PbO ZrO_2, $CaWO_4$ Iodoform	Pure PC	All OPC compositions had acceptable radiopacity
Saliba *et al*. [70]	*In vitro*	WPC	10, 15, 20, 25,30% Bi_2O_3	WPC	Addition of Bi_2O_3 did not affect the compressive strength of PC
Hwang *et al*. [94]	*In vitro*	PC	Bi_2O_3	MTA	OPC had radiopacity similar to MTA, MTA had higher cell viability than OPC
Bueno *et al*. [63]	*In vitro*	WPC	Bi_2O_3	WMTA	MTA and PC+15% Bi_2O_3 had similar radiopacity
Coutinho *et al*. [60]	Animal study	PC	Bi_2O_3	ProRoot MTA	All materials were biocompatible during 60 days
Kim *et al*. [190]	*In vitro*	PC	Bi_2O_3	-	PC+20% Bi_2O_3 had the most radiopacity and similar cell viability to PC+ less concentrations of Bi_2O_3

Note: PC: Portland cement, WPC: white Portland cement, BG: BioGlass, CSC: calcium silicate cement.

6.1. Bismuth Oxide

MTA is predominantly composed of Portland cement with the addition of bismuth oxide as a radiopacifier [58]. Addition of various percentages of bismuth oxide up to 50% to Portland cement did not influence the alkaline pH of the cement [59]. Moreover, Portland cement radiopacity has a correlation with the concentration of incorporated bismuth oxide, although the cytotoxicity issues must be considered [60]. Radiopacity of white Portland cement with bismuth oxide (20%) does not show a significant difference with that of aluminum with 4 mm thickness, which is the ideal value according to the American National Standard Institute/American Dental Association (ANSI/ADA) recommendations [56, 61, 62]. Bueno *et al*. reported that the ideal concentration of bismuth oxide to provide radiopacity similar to MTA is 15% [63].

It is noteworthy that the addition of bismuth oxide seems to compromise the physical properties of the material. The particle size of bismuth oxide also affects these properties as reducing the particle size of bismuth oxide increases the diametral tensile strength significantly [64]. Bismuth oxide increases the porosity of Portland cement and consequently reduces the compressive strength and extends the setting time [65 - 67]. Comparing the influence of the addition of various radiopacifiers to Portland cement on its compressive strength showed that only the incorporation of bismuth oxide resulted in lower compressive strength [68]. Nevertheless, in this study radiopaque Portland cement had reduced initial and final setting times. Bismuth oxide concentration has a negative correlation with mechanical strength and increases the relative porosity of set material [69]. In contrast, Saliba *et al*. showed that Portland cement's compressive strength was not affected by the addition of various percentages of bismuth oxide [70]. According to Bosso-Martelo *et al*., amongst various radiopacifiers only bismuth oxide did not affect the final setting time of Portland cement, although it was significantly more than the setting time of MTA Angelus [55].

Furthermore, there are conflicting results regarding the impact of bismuth oxide on the solubility of Portland cement. According to Weckwerth *et al*., bismuth oxide affects this property adversely [71], whereas some studies indicated that radiopaque Portland cement exhibits less mass loss following immersion in water compared to MTA [66, 72]. It should be

taken into consideration that the curing and experiment conditions affect the physical properties of cement significantly. For instance, bismuth oxide modified Portland cement has higher compressive strength when immersed in distilled water, although it shows lower compressive strength in Hank's balanced salt solution (HBSS) [73].

6.2. Zirconium Oxide

Studies have shown that the fabrication of Portland cement associated with zirconium oxide as a radiopacifier might be preferred to bismuth oxide since no significant adverse effect was detected concerning the physical properties such as compressive strength and solubility and biological activities [66 - 68]. Some studies reported similar radiopacity for Portland cement containing zirconium oxide micro or nanoparticles and Portland cement containing bismuth oxide [55, 74]. Studies showed that the inclusion of 30 wt% zirconium oxide to Portland cement results in acceptable compressive strength without compromised hydraulic properties, suggesting zirconium oxide as a potential alternative to bismuth oxide [74 - 77]. Furthermore, a combination of 30 wt% zirconium oxide and Portland cement promotes its radiopacity, setting time and solubility similar to ProRoot MTA [78]. The same results were achieved by Bosso-Martelo *et al*. [55]. In contrast, a longer setting time was observed by Duarte *et al*. following the addition of 20 wt% zirconium oxide to white Portland cement with a considerable difference to white MTA, which seems to be related to the amount of calcium sulfate in this material [66]. This study reported limited calcium release from radiopaque Portland cement (containing zirconium oxide, bismuth oxide or calcium tungstate) compared to pure white Portland cement, however, it was not different from the calcium release of white MTA in the first hours. Zirconium oxide does not interfere with hydration by-products of Portland cement and acts as an inert filler. Moreover, it provides efficient nucleation sites for the precipitation and growth of the calcium-silicate-hydrate (C-S-H) gel phase resulting in an increase in hydration degree by 26% [65, 75 - 79]. SEM evaluation of zirconium oxide modified Portland cement revealed free zirconium oxide particles distributed throughout the cement [75]. In agreement with these studies, Li *et al*. reported that zirconium oxide did not participate in chemical reactions of Portland cement hydration and decreased the solubility of cement without affecting its calcium release capacity [80].

6.3. Ytterbium Trifluoride

Ytterbium trifluoride seems to be a potential radiopacifier to be incorporated into Portland cement with no significant adverse effect on its mechanical and biological properties [81]. The addition of 20 wt% ytterbium trifluoride resulted in a radiopacity value equal to 3 mm Al cut-off and promoted the compressive strength of Portland cement [67]. Incorporation of fluoride in Portland cement and long-term sustained release of it might have beneficial effects on the prevention of caries and improvement of osteogenesis, dentinogenesis (to enhance apexogenesis and apexification) and mechanical properties of dentin by the formation of fluorapatite. However, it is worth mentioning that, excessive fluoride accumulation interferes with hard tissue formation and might cause cytotoxic issues for root-end filling material. Noticeable release of Yb and F ions from ytterbium trifluoride containing Portland cement leads to an increased risk of cytotoxicity [81]. Notably, the low water solubility of ytterbium trifluoride may limit the long-term degradation of dental cement. This is of particular importance in preserving the structural integrity of the tooth for treatment success.

6.4. Niobium Oxide

Another alternative for bismuth oxide considered in the literature is niobium oxide micro and nanoparticles [10, 82, 83]. Recent researches also showed that niobium might stimulate hydroxyapatite deposition. Addition of microparticulate and nanoparticulate niobium oxide to Portland cement results in a material with satisfactory physicochemical and biological characteristics in terms of setting time and radiopacity and provides an alkaline environment. This study also indicated that the particle size did not have a significant effect on the physicochemical and biological properties of the cement [84]. Although higher radiopacity was demonstrated by MTA compared to Portland cement containing niobium oxide, greater cell viability and alkaline phosphatase activity were detected by this combination [85]. Niobium oxide modified Portland cement showed setting time, flowability, compressive strength and solubility adequate for clinical applications [86].

6.5. Other Radiopacifiers

Other radiopacifiers, such as 15% bismuth carbonate and calcium tungstate, have been incorporated into Portland cement and showed adequate pH level, calcium release and radiopacity similar to MTA [66, 87]. The addition of 15% bismuth carbonate to Portland cement did not influence its solubility but increased the setting time [87]. Studies have demonstrated that Portland cement containing 20% iodoform shows sufficient radiopacity to address the current regulatory standards for root filling materials [88, 89]. Other radiopacifiers, including lead oxide, bismuth subnitrate, tantalum oxide and barium sulfate, have been incorporated into Portland cement with higher radiopacity than dentin or pure Portland cement [56, 77, 90]. Furthermore, addition of barium sulfate or silver alloy exhibited acceptable radiopacity and induced a PH increase. Although these materials extended the setting time, no adverse effect was observed regarding the compressive strength [91].

6.6. Biocompatibility of Portland Cement with Different Radiopacifiers

6.6.1. In vitro Studies

The aforementioned additives might influence the biocompatibility of cement and interfere with the healing of the periapical tissues. In a biological point of view, radiopacifying agents with excellent safety profiles and good biocompatibility are commonly chosen. Cell culture studies, in addition to morphologic analysis, reported no cytotoxicity of white Portland cement containing bismuth oxide, zirconium oxide and calcium tungstate against murine periodontal ligament cells and rat osteosarcoma cells up to a concentration of 100 mg/ml. Although the presence of heavy metals in higher

concentrations can promote necrosis cell death due to oxidative stress [92]. White Portland cement containing zirconium oxide or zinc oxide exhibited acceptable cell viability and increased ALP activity of hDPSCs during a 21 days period [93].

Some previous studies found similar bioactivity, cytotoxicity, genotoxicity and tissue reaction among pure Portland cement, bismuth oxide containing Portland cement and MTA [94 - 96]. The addition of various amounts of bismuth oxide to Portland cement up to 50% does not affect its biocompatibility, although the concentration of 15% bismuth oxide shows a significant decrease in the inflammatory response [59]. A modified Bi_2O_3-radiopacifier (zirconia doped bismuth oxide) was incorporated into Portland cement by Chen *et al*. in order to improve the radiopacity of the material to approximately 6 mm Al. The desirable biocompatibility of this compound satisfies the requirements for a potential root filling material [97].

Furthermore, according to Min *et al*., radiopaque and pure Portland cement have similar effects on the mineralization of hDPCs [98]. This *In vitro* study observed well-spread hDPSCs with cellular extensions in close contact with radiopaque Portland cement in addition to increased ALP activity and high expression of osteogenic markers (osteonectin and dentin sialophosphoprotein). Evaluation of cytotoxicity of 15% bismuth carbonate-containing Portland cement on human periodontal ligament fibroblasts (hPLFs) showed noticeable biocompatibility [87]. Further assessment of the expression of bone formation genes (ALP, COL1 and RUNX2) and pro-inflammatory cytokines (IL-1A, IL-6, IL-8 and TNF) resulted in similar findings to MTA [87].

Regarding the addition of Ytterbium trifluoride to Portland cement, *In vitro* studies have reported no adverse effect on the differentiation of bone marrow mesenchymal stem cells and the morphology of osteoblasts and osteoclasts following cell culture. Furthermore, numerous cell extensions were detected, implying appropriate cell spreading and adherence to the substrate [81].

6.6.2. Animal Studies

Although *In vitro* studies have shown satisfying bioactivity of radiopaque Portland cement, in an animal study, Dreger *et al*. observed that MTA is more effective in promoting biomineralization in the dentin-cement interface and the intratubular space. This study reported more rapid and intense mineral deposition in MTA cases compared to Portland cement with 20% bismuth oxide [99].

Implantation of Portland cement associated with radiopacifiers, including iodoform or zirconium oxide, into the dorsal connective tissue of rats also showed no significant difference in the inflammatory response from pure Portland cement, however, morphological analyses revealed less inflammation in radiopaque groups [88]. In a similarly designed study, no difference in terms of tissue reaction was detected between Portland cement containing 20% iodoform or zirconium oxide or bismuth oxide and MTA [90]. Adversely, Silva *et al*. demonstrated that radiopacifier agents induced inflammatory reactions significantly, and this increase was higher in Portland cement containing bismuth oxide in comparison with Portland cement with zirconium oxide [74].

6.6.3. Clinical Studies

Clinical and subsequent histological analyses of pulp tissues following the application of Portland cement containing zirconium oxide or iodoform showed no inflammatory response and granulation tissue during the 24-month follow-up [31, 32].

7. MODIFICATION OF PORTLAND CEMENT WITH CALCIUM CHLORIDE

Incorporation of calcium chloride up to 15% changes the surface morphology of white Portland cement and results in a more homogenous surface with less porosity which reduces bacterial contamination and favors biological properties [53]. Furthermore, it reduces the setting time of Portland cement and MTA by altering the kinetics of tricalcium silicate hydration [100], improves the sealing ability [101] and push-out strength [102], increases PH [103], reduces the solubility [103] and does not affect the dimensional stability [104]. Moreover, calcium chloride modified Portland cement possesses adequate compressive strength for orthopedic applications [47]. The calcium silicate cements with calcium chloride release more calcium ions and increase pH immediately, although no difference was observed in the other intervals [105]. The addition of calcium carbonate and calcium chloride combination to MTA (Portland cement containing bismuth oxide) also showed a shorter setting time compared to MTA Angelus and ProRoot MTA [58].

In vitro evaluation of biocompatibility and bioactivity of Portland cement containing calcium chloride has shown no cytotoxicity against stem cells from human exfoliated deciduous teeth at concentrations <12.5 mg/ml [96, 106]. In contrast, fast-set Portland cement has high cytotoxicity against hDPSCs [53]. Implantation of dentin tubes containing Portland cement with 10% calcium chloride in the subcutaneous tissue of rats resulted in biomineralization in the dentin-cement interface [99]. Portland cement containing 3 wt% calcium chloride exhibited the most bioactivity and the highest apatite forming ability when immersed in simulated body fluid (SBF) solution [107].

8. MODIFICATION OF PORTLAND CEMENT WITH GRAPHENE OXIDE

Portland cement reinforced with carbon-based nanomaterials such as carbon nanofibers, multiwalled carbon nanotubes and graphene oxide nanoplatelets has shown improved fracture toughness and water-resistant properties with decreased porosity [108, 109]. Graphene oxide accelerates Portland cement hydration process by improving crystal growth and providing a nucleation effect. Graphene oxide accelerates the formation of C_3S, which is responsible for the early strength of the material, although it has been reported to affect the hydration of C_3A more perceptibly than C_3S [110, 111]. The incorporation of 0.1% graphene oxide increases Portland cement hydration degree up to 10.4% in 28 days [112]. The carboxyl acid groups of graphene oxide can bond covalently with C-S-H and improve the mechanical properties

of cement. Furthermore, graphene oxide acts as a reinforcing filler and decreases cement's porosity and permeability, prevents propagation of cracks and presents an abrasion-resistant dense microstructure [6, 110, 113]. Graphene oxide can improve the compressive strength of Portland cement by 33% and its flexural strength by 59% [114]. Moreover, it has been reported to increase the compressive strength of Portland cement by 46% and its tensile strength by 53% [115]. The addition of 0.1 wt% nano-graphene oxide increases the compressive strength of Portland cement from 54.2 MPa to 84.5 MPa, which is about 55.8% [113].

The incorporation of 5% graphene oxide into various bioactive calcium silicate cement improves the mineralization significantly and does not affect the proliferation of hDPSCs [116]. Another study revealed that calcium silicate ceramic composites reinforced with graphene oxide nanoplatelets have acceptable apatite forming ability, biocompatibility and also promote the viability and proliferation of human osteoblast cells [117]. The addition of 1 wt% graphene oxide nanoparticles to Portland cement improves its microhardness without affecting its biocompatibility [118]. On the whole, the addition of graphene oxide to Portland cement exhibits beneficial effects on its workability and durability, however, further investigations on the biocompatibility of this material are required to be applied in clinical studies.

9. MODIFICATION OF PORTLAND CEMENT WITH CARBON NANOTUBES

Single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) are promising reinforcements for tissue engineering and producing cementitious materials due to their multi-functional properties. Provided well dispersion of nanotubes in the cement matrix, CNTs act as a filler and produce a denser material and prevent crack propagation [119]. Moreover, CNTs affect the cement by bridging between hydration products and consequently enhancing composite toughness [120, 121]. Another consideration in this regard is that CNTs act as nucleation sites for hydration products resulting in a high percentage of C-S-H and portlandite [122]. Despite conflicting results in early works on CNTs-modified Portland cement, predominant studies agree on improved flexural [9], compressive [9, 123] and tensile strength [124] and modulus of elasticity [125] following the addition of CNTs to Portland cement [126].

10. MODIFICATION OF PORTLAND CEMENT WITH NANO-SILICA

Another nanoparticle to be introduced into Portland cement to enhance its performance in terms of workability and long-term durability is nano-silica. Nano-silica particles act as a filler in the paste and provide nucleation sites, thus accelerate cement's hydration process. On the other hand, it affects cement characteristics by undertaking a pozzolanic reaction, which further intensifies C-S-H gel growth and densifies the final cement [127 - 129]. The hydration rate of cement depends on the surface area of added silica particles and the pattern of dispersion. Although, in recent years, attention has been widely paid to the impact of nanoparticles on the hydration of C_3S, few studies showed that nano-silica can improve the hydration of C_3A with a decrease in the heat release rate during the process [130]. Notwithstanding, further exploration is required for a better understanding of the influence of silica on the hydration mechanism of C_3S and C_3A. It is well known that nano-silica containing cement presents a shorter setting time, reduced formation of calcium hydroxide, dense and impact microstructure and superior mechanical properties [131]. The addition of nano-silica to Portland cement was found to improve its compressive, flexural and split tensile strength in a concentration-dependent manner [132, 133]. Shih *et al*. found that the addition of 0.6 wt% nano-silica results in an increase in the compressive strength of Portland cement (water/cement ratio of 0.55) by 43.8% [134]. Furthermore, the addition of nano-silica to MTA was shown to reduce the setting time and increase the compressive and flexural strength in 7 days, although changes were not significant [135]. Despite the wide investigation of the rheological and mechanical properties of nano-silica-contained Portland cement, the biocompatibility and bioactivity of this composition require further studies.

11. MODIFICATION OF PORTLAND CEMENT WITH HYDROXYAPATITE

Calcium silicate cement reinforced with hydroxyapatite are biointeractive materials with apatite forming ability and are great candidates for bone substitute materials [136 - 138]. Evaluation of biocompatibility and inflammation response in vivo showed more acceptable results for hydroxyapatite-containing cement compared to uncoated ones [137]. The incorporation of hydroxyapatite into tricalcium silicate cement has also been reported to reduce its genotoxicity [139]. The addition of nano-hydroxyapatite to Portland cement affects the hydration process and results in decreased compressive strength, although after immersion in SBF solution for 4 weeks and precipitation of bone-like apatite compressive strength increases [140]. Dasgupta *et al*. assessed the possessions of Portland cement by adding micro and nanoparticles of hydroxyapatite and observed better physical, mechanical and biological properties for the material with particle sizes of 168 nm. Then, according to their results, the addition of nano-hydroxyapatite could be an option for improving the properties of the calcium silicate-based cement [141]. Furthermore, Tanomaru *et al*. reported that the addition of hydroxyapatite to Portland cement affected negatively on compressive strength and solubility of the cement, however, the antibacterial property was improved [142].

12. MODIFICATION OF PORTLAND CEMENT WITH NANO-CALCIUM CARBONATES

Nano calcium carbonate has finer particles with more surface area compared to micro calcium carbonate and thus affects more on hydration process and mechanical properties [143]. The addition of calcium carbonate nanoparticles to Portland cement accelerates the setting process and reduces the initial and final setting times and the water needed for cement hydration and also improves mechanical resistance without altering solubility or dimensional stability [143 - 145]. Calcium carbonate shortens the induction period of the hydration process by nucleation effect and accelerating the formation of ettringite. It has been reported that the incorporation of 1%

nano-calcium carbonate into Portland cement results in the optimal performance of cement as it increases the compressive strength of Portland cement by 7% after 56 days and reduces the permeability by 13% and shrinkage by 66% [146, 147]. Further increase in calcium carbonate concentration might affect the compressive strength adversely due to the increased amount of harmful pores [148]. Overall, the modification of cement characteristics depends on the content and particle size of added calcium carbonate [147].

13. RESIN-MODIFIED PORTLAND CEMENT

Due to many drawbacks of MTA and Portland cement, more importantly, their poor bonding to resins, resin-modified Portland cement was introduced in 2011. TheraCal is a hydraulic silicate cement composed of 45% Portland cement type III, 43% resin and variable amounts of fumed silica and radiopacifiers, including barium sulfate and bismuth oxide [149, 150]. TheraCal releases a significant amount of calcium ions throughout 28 days and alkalinizes its environment up to pH 11, which decreases to pH 8.5 during 14 days. Furthermore, it has significantly less solubility than ProRoot MTA and Dycal [151]. The resin matrix of TheraCal alters its setting mechanism and amount of calcium ion release, however, it is in a concentration range to promote the proliferation and differentiation of hDPCs and the formation of mineralized hard tissue [152, 153]. TheraCal has satisfactory compressive and push-out bond strength to dentin and microshear bond strength to different restorative materials, which were significantly superior to MTA and Dycal [154 - 156]. *In vitro* evaluation of biocompatibility and bioactivity of set TheraCal on hDPSCs showed that although TheraCal promoted the mineralization after 21 days, it exhibited low cell proliferation, slower cell migration and ALP activity compared to Biodentin [157 - 159]. The re-mineralization speed of TheraCal is less than resin-free hydraulic calcium silicate cement [160]. Moreover, the amount of necrotic cells associated with TheraCal is higher compared to other Portland cement-based pulp capping materials [161]. Clinical and animal studies investigating TheraCal are listed in Table **2**. Considering all aspects, it seems that resin-free Portland cement have shown more satisfactory results concerning biocompatibility and clinical applications such as vital pulp therapy.

Table 2. Clinical and animal studies on applications of resin-modified Portland cement (TheraCal).

Refs.	Other Groups	Application	Teeth	Treatment Period	Clinical/Radio-Graphical Observations	Histological Evaluations
Human Studies						
Bakhtiar *et al*. [191]	Biodentin ProRoot MTA	Partial Pulpotomy	Third molars	8 weeks	TheraCal had a success rate of 80%	Incomplete dentin bridge formation was detected in the TheraCal group, no pulp inflammation was detected except for one in the TheraCal group Only 11.11% of the TheraCal group had normal pulp organization
Gurcan *et al*. [192]	Dycal ProRoot MTA	Indirect pulp capping	First Permanent molars/ Second primary molars	2 years	TheraCal had a success rate of 87.7% (No difference between groups)	-
Erfanparast *et al*. [193]	MTA	Direct pulp capping	Primary molars	1 year	TheraCal had a 91.8% success rate (No difference between groups)	-
Cengiz *et al*. [194]	$Ca(OH)_2$	Direct pulp capping	Premolar/molar	6 months	TheraCal had a 66.6% success (No difference with $Ca(OH)_2$)	-
Menon *et al*. [195]	MTA	Indirect pulp capping	Primary molars	6 months	No significant difference between groups in dentin forming	-
Alqahtani *et al*. [196]	$Ca(OH)_2$	Direct/Indirect pulp capping	-	3 months	TheraCal had a success rate of 85.5% (No difference between groups)	-
Peskersoy *et al*. [197]	Biodentin Dycal MTA	Direct pulp capping	-	36 months	TheraCal had 72.1% and 73.6% clinical and radiographical success rate (No difference with dycal)	-
Sahin *et al*. [198]	Dycal Biodentin	Indirect pulp capping	Primary molars	24 months	TheraCal had a 93.3% success rate (No difference between groups)	TheraCal formed an incomplete odontoblastic layer and showed pulpitis
Animal studies						

(Table 2) contd.....

Refs.	Other Groups	Application	Teeth	Treatment Period	Clinical/Radio-Graphical Observations	Histological Evaluations
Cannon *et al*. [199]	Pure PC Resin-based $Ca(OH)_2$ GI	Pulp capping	-	4 weeks	Complete hard tissue formation in PC and TheraCal group	TharaCal and PC formed the thickest dentin bridge
Lee *et al*. [200]	ProRoot MTA RetroMTA	Partial Pulpotomy	-	4 weeks	-	TheraCal group showed lower dentin bridge formation, extensive inflammation, less osteocalcin and dentin sialoprotein expression
Li *et al*. [201]	ProRoot	Direct pulp capping	-	70 days	No significant tooth discoloration	Mineralized tissue was detected beneath the exposed pulp with no inflammatory response
Hinata *et al*. [202]	MTA Prototype CSC	Subcutaneous implantation	-	28 days	-	Ca and P containing apatite-like surface precipitated with the least thickness compared to other groups

14. OTHER MODIFICATIONS

Quaternary ammonium compounds are widely used in medicine due to their high antimicrobial efficacy as well as low cytotoxicity and biological effects. The incorporation of quaternary ammonium into dental adhesive systems and endodontic cement has beneficial effects on antimicrobial and mechanical properties and biocompatibility [162]. Light cured resin-modified Portland cement containing quaternary ammonium salt has been introduced as a pulp capping material with acceptable antibacterial activity [163]. This material showed better alkalinizing activity and calcium release ability compared to Dycal during 28 days after curing, although pH value and calcium release amount decreased over time. The modified Portland cement had acceptable cytotoxicity against hDPFs and apatite forming ability in phosphate buffered saline [164]. Furthermore, it enhanced the adhesion and migration of hDPSCs and the expression of osteogenesis-related genes. HDPSCs showed higher alkaline phosphatase activity and calcium deposition when cultured with quaternary ammonium-modified Portland cement [165].

Superplasticizers are fundamental additives in concrete production to control cement performance since they strongly influence concrete rheology properties. Among various generations of superplasticizers, polycarboxylate with spectacular properties has been evaluated for dental applications [166]. The unique structure of polycarboxylate allows applying modifications to its functional group, main chain or side chains in order to achieve the expected performance from Portland cement [167]. Polycarboxylate-modified Portland cement has a short setting time in the range of 4-11 minutes and presents more flowability in a very low water:cement ratio [168]. On the whole, the addition of superplasticizers improves the workability of Portland cement and leads to a rapid increase in the formation of high-strength cement with low permeability [169].

Another modification to the chemical structure of Portland cement is the addition of chitosan, which has been reported to improve the handling properties of cement [170]. It should be noticed that the influence of chitosan derivatives on the behavior of Portland cement strongly depends on the main substitution group of the derivative [171]. Chitosan crystallites spread through the material structure, fill the pores and provide a homogenous morphology, which in turn improves the biological characteristics of the cement by promoting cell adhesion and spreading. Chitosan-modified Portland cement exhibited good mechanical properties with improved solubility and extended setting time. However, compressive strength showed a decrease dependent on the chitosan content [172]. Furthermore, chitosan containing Portland cement exhibited less heavy metal leaching [173]. Carboxymethyl chitosan also acts as an anti-washout additive and extends the setting time of tricalcium silicate cement. This novel bone cement presents good bioactivity with the deposition of crystalline apatite [174]. Chitosan and dicalcium phosphate showed a synergistic effect on the apatite forming ability of Portland cement [170]. Kamali *et al*. added chitosan and zirconium oxide to Portland cement as a substitute for MTA. In this study, malic acid-containing chitosan composed the liquid phase. Malic acid reacted with free amino groups of chitosan and consequently provided expanded polymer chains, which allowed the enhanced formation of hydration by-products within the polymer chains [175].

Geopolymer is a kind of amorphous aluminosilicate with satisfying physical and mechanical properties and durability due to the polymerization reaction [176]. The apatite formation ability of geopolymer when immersed in SBF solution shows the potential of this material to be used in bioenviroments [177, 178]. Modification of white Portland cement with aluminosilicate materials such as calcined kaolin geopolymer system produces a favorable bone repair material with rapid setting and high compressive strength. Furthermore, this system exhibited good bioactivity when exposed to SBF solution and promoted hydroxyapatite precipitation [179, 180]. Fig. (**1**) shows various applications of Portland cement in dentistry.

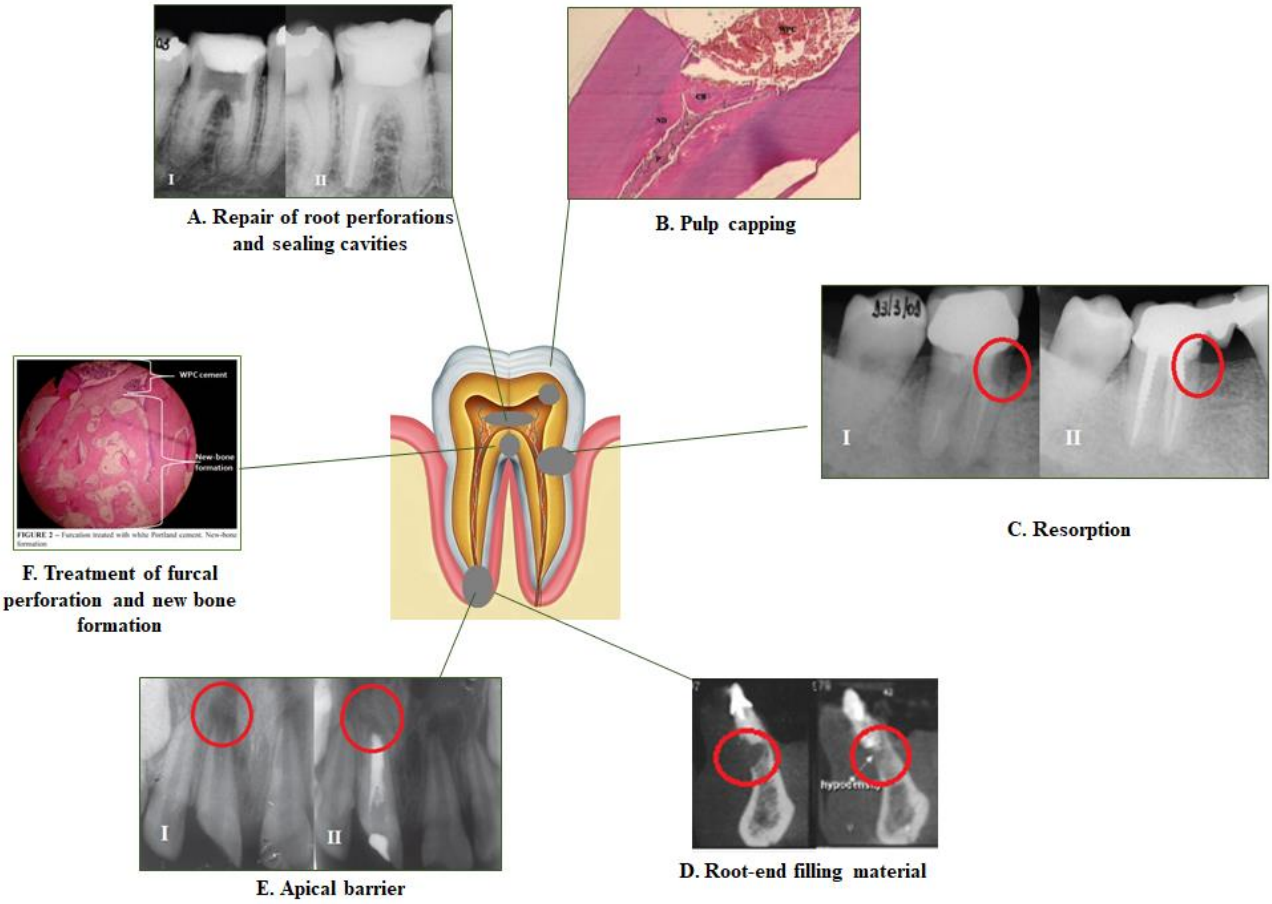

Fig. (1). Various applications of Portland cement in dentistry. (**A**) Radiographic evaluation of treatment of root perforation using PC after 9 years; Note the radiographic repair with no radiolucency in the periodontal region [14] Available online under a Creative Commons license Attribution-Non Commercial-No-Derivatives 4.0 International (CC BY-NC-ND 4.0). (**B**) Histological evaluation of pig's pulp tissue following pulp capping by PC; A complete calcified bridge is formed and the pulp tissue presents a normal condition free of inflammation [17] Available online under a Creative Commons license Attribution. (**C**) Radiographic evaluation of treatment of resorption area using PC shows root repair after 11 year [14] Available online under a Creative Commons license Attribution-Non Commercial-No-Derivatives 4.0 International (CC BY-NC-ND 4.0). (**D**) Application of PC as a root-end filling material after periapical surgery; Periradicular tissue regeneration is obvious after 6 months [15] Available online under a Creative Commons license Attribution-Non Commercial-No-Derivatives 4.0 International (CC BY-NC-ND 4.0). (**E**) Radiographic evaluation of apex of 11 following using PC as an apical plug; Note the total repair after 5 months [33] Available online under a Creative Commons license Attribution-Non Commercial-No-Derivatives 4.0 International (CC BY-NC-ND 4.0). (**F**) Histological evaluation of furcal perforation using PC; New bone formation with normal pulp conditions are detectable [13] Available online under a Creative Commons license Attribution-Non Commercial-No-Derivatives 4.0 International (CC BY-NC-ND 4.0)..

CONCLUSION

As a biocompatible bioactive endodontic cement with favorable characteristics and a wide range of applications, Portland cement and its derivatives have been under multiple investigations, although extensive issues are still open for further research. As reported in this review, a significant attempt has been made to extend the application scope of Portland cement with various modifications, such as the inclusion of polymers, radiopacifiers, metal oxides, superplasticizers and nanomaterials, namely nano-silica, titanium oxide and calcium carbonate. Consequently, various MTA types and resin-modified Portland cement have been introduced. In the dentistry field, Portland cement is widely serviceable in restorative dentistry and particularly in different kinds of endodontic treatments. We can conclude that Portland cement has the potential to be used as an acceptable pulp capping material with the least complaints in the long term. The addition of radiopacifiers can contribute to improve the utilization efficacy of Portland cement. Given the valuable properties of Portland cement and its low price compared to MTA, considering it as an alternative to MTA seems to be beneficial. Nonetheless, the key issue is bringing the various modified Portland cement into clinical practice and evaluating them in the bioenvironment. Besides, it has been reported that some toxic heavy metals such as chromium and lead are released from Portland cement. This can be of concern when Portland cement is in contact with hard and soft tissues and should be considered a subject for future studies.

LIST OF ABBREVIATIONS

MTA = Mineral Trioxide Aggregate

HBSS = Hank's Balanced Salt Solution

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REFERENCES

[1] Fayazi S, Razmi H, Ostad SN. Effect of ProRoot MTA, Portland cement, and amalgam on the expression of fibronectin, collagen I, and TGFβ by human periodontal ligament fibroblasts *in vitro*. Indian J Dent Res 2011; 22(2): 190-4. [http://dx.doi.org/10.4103/0970-9290.84278] [PMID: 21891883]

[2] Al-Hezaimi K, Salameh Z, Al-Fouzan K, Al Rejaie M, Tay FR. Histomorphometric and micro–computed tomography analysis of pulpal response to three different pulp capping materials. J endodont 2011; 37(4): 507-12.

[3] Korkmaz AV. Mechanical activation of diabase and its effect on the properties and microstructure of Portland cement. Case Studies Construc Mat 2022; 16: e00868. [http://dx.doi.org/10.1016/j.cscm.2021.e00868]

[4] Kawashima S, Hou P, Corr DJ, Shah SP. Modification of cement-based materials with nanoparticles. Cement Concr Compos 2013; 36: 8-15. [http://dx.doi.org/10.1016/j.cemconcomp.2012.06.012]

[5] Paul SC, van Rooyen AS, van Zijl GPAG, Petrik LF. Properties of cement-based composites using nanoparticles: A comprehensive review. Constr Build Mater 2018; 189: 1019-34. [http://dx.doi.org/10.1016/j.conbuildmat.2018.09.062]

[6] Chintalapudi K, Pannem RMR. The effects of Graphene Oxide addition on hydration process, crystal shapes, and microstructural transformation of Ordinary Portland Cement. J Build Eng 2020; 32: 101551. [http://dx.doi.org/10.1016/j.jobe.2020.101551]

[7] Evangelista ACJ, de Morais JF, Tam V, Soomro M, Di Gregorio LT, Haddad AN. Evaluation of carbon nanotube incorporation in cementitious composite materials. Materials 2019; 12(9): 1504. [http://dx.doi.org/10.3390/ma12091504] [PMID: 31072039]

[8] Jee H, Park J, Zalnezhad E, *et al.* Characterization of titanium nanotube reinforced cementitious composites: Mechanical properties, microstructure, and hydration. Materials 2019; 12(10): 1617. [http://dx.doi.org/10.3390/ma12101617] [PMID: 31100956]

[9] Xu S, Liu J, Li Q. Mechanical properties and microstructure of multi-walled carbon nanotube-reinforced cement paste. Constr Build Mater 2015; 76: 16-23. [http://dx.doi.org/10.1016/j.conbuildmat.2014.11.049]

[10] Tanomaru JMG, Storto I, Da Silva GF, *et al.* Radiopacity, pH and antimicrobial activity of Portland cement associated with micro-and nanoparticles of zirconium oxide and niobium oxide. Dent Mater J 2014; 1: 2013-328.

[11] Juárez Broon N, Bramante CM, Assis GF, *et al.* Healing of root perforations treated with Mineral Trioxide Aggregate (MTA) and Portland cement. J Appl Oral Sci 2006; 14(5): 305-11. [http://dx.doi.org/10.1590/S1678-77572006000500002] [PMID: 19089049]

[12] Silva Neto JD, Schnaider TB, Gragnani A, Paiva AP, Novo NF, Ferreira LM. Portland cement with additives in the repair of furcation perforations in dogs. Acta Cir Bras 2012; 27(11): 809-14. [http://dx.doi.org/10.1590/S0102-86502012001100011]

[13] Silva Neto JD, Brito RH, Schnaider TB, Gragnani A, Engelman M, Ferreira LM. Root perforations treatment using mineral trioxide aggregate and Portland cements. Acta Cir Bras 2010; 25(6): 479-84. [http://dx.doi.org/10.1590/S0102-86502010000600004]

[14] Borges ÁH, Bandeca MC, Tonetto MR, *et al.* Portland cement use in dental root perforations: a long term followup. Case Rep Dent 2014; 2014: 1-5. [http://dx.doi.org/10.1155/2014/637693] [PMID: 24715998]

[15] Silva SR, Silva Neto JD, Veiga DF, Schnaider TB, Ferreira LM. Portland cement *versus* MTA as a root-end filling material. A pilot study. Acta Cir Bras 2015; 30(2): 160-4. [http://dx.doi.org/10.1590/S0102-865020150020000011] [PMID: 25714696]

[16] Bidar M, Naghavi N, Mohtasham N, *et al.* Mineral trioxide aggregate and portland cement for direct pulp capping in dog: a histopathological evaluation. J Dent Res Dent Clin Dent Prospect 2014; 8(3): 134-40. [PMID: 25346831]

[17] Shayegan A, Petein M, Vanden Abbeele A. The use of beta-tricalcium phosphate, white MTA, white Portland cement and calcium hydroxide for direct pulp capping of primary pig teeth. Dent Traumatol 2009; 25(4): 413-9. [http://dx.doi.org/10.1111/j.1600-9657.2009.00799.x] [PMID: 19519859]

[18] Barbosa AVH, Sampaio GC, Gomes FA, Oliveira DP, Albuquerque DS, Sobral APV. Short-term analysis of human dental pulps after direct capping with portland cement. Open Dent J 2009; 3(1): 31-5. [http://dx.doi.org/10.2174/1874210600903010031] [PMID: 19444341]

[19] Menezes R, Bramante CM, Letra A, Carvalho VGG, Garcia RB. Histologic evaluation of pulpotomies in dog using two types of mineral trioxide aggregate and regular and white Portland cements as wound dressings. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2004; 98(3): 376-9. [http://dx.doi.org/10.1016/j.tripleo.2004.03.008] [PMID: 15356480]

[20] Menezes R, Bramante CM, Garcia RB, *et al.* Microscopic analysis of dog dental pulp after pulpotomy and pulp protection with mineral trioxide aggregate and white Portland cement. J Appl Oral Sci 2004; 12(2): 104-7. [http://dx.doi.org/10.1590/S1678-77572004000200004] [PMID: 21365130]

[21] Holland R, de Souza V, Murata SS, *et al.* Healing process of dog dental pulp after pulpotomy and pulp covering with mineral trioxide aggregate or Portland cement. Braz Dent J 2001; 12(2): 109-13. [PMID: 11445912]

[22] Shayegan A, Petein M, Abbeele AV. Beta-tricalcium phosphate, white mineral trioxide aggregate, white Portland cement, ferric sulfate, and formocresol used as pulpotomy agents in primary pig teeth. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2008; 105(4): 536-42. [http://dx.doi.org/10.1016/j.tripleo.2007.10.008] [PMID: 18329589]

[23] Sakai VT. Pulpotomy of human primary molars with MTA and Portland cement: A randomised controlled trial. British Dent J 2009; 207(3): E5.

[24] Oliveira TM, Moretti ABS, Sakai VT, *et al.* Clinical, radiographic and histologic analysis of the effects of pulp capping materials used in pulpotomies of human primary teeth. Eur Arch Paediatr Dent 2013; 14(2): 65-71. [http://dx.doi.org/10.1007/s40368-013-0015-x] [PMID: 23549993]

[25] Yildirim C, Basak F, Akgun OM, Polat GG, Altun C. Clinical and radiographic evaluation of the effectiveness of formocresol, mineral trioxide aggregate, Portland cement, and enamel matrix derivative in primary teeth pulpotomies: a two year follow-up. J Clin Pediatr Dent 2016; 40(1): 14-20. [http://dx.doi.org/10.17796/1053-4628-40.1.14] [PMID: 26696101]

[26] Vilimek VM, Gateva N, Christof BS. Success rate of MedCem Portland cement as a pulp capping agent in pulpotomies of primary teeth. J IMAB Annual Proceed Sci Paper 2018; 24(1): 1866-71.

[27] Maroto M, Barreiro S, Barbería E. Portland cement as pulp dressing agent in pulpotomy treatment of primary molars: a 12-month clinical study. Eur J Paediatr Dent 2019; 20(1): 23-6. [PMID: 30919640]

[28] Conti TR, Sakai VT, Fornetti APC, *et al.* Pulpotomies with portland cement in human primary molars. J Appl Oral Sci 2009; 17(1): 66-9. [http://dx.doi.org/10.1590/S1678-77572009000100013] [PMID: 19148409]

[29] Petel R, Ziskind K, Bernfeld N, Suliman H, Fuks A, Moskovitz M. A randomised controlled clinical trial comparing pure Portland cement and formocresol pulpotomies followed from 2 to 4 years. Eur Arch Paediatr Dent 2020; 2: 1-6.

[PMID: 33175326]
[30] Bhagat D, Sunder R, Devendrappa S, Vanka A, Choudaha N. A comparative evaluation of ProRoot mineral trioxide aggregate and Portland cement as a pulpotomy medicament. J Indian Soc Pedod Prev Dent 2016; 34(2): 172-6.
[http://dx.doi.org/10.4103/0970-4388.180448] [PMID: 27080969]
[31] Marques N, Lourenço Neto N, Fernandes AP, *et al.* Pulp tissue response to Portland cement associated with different radio pacifying agents on pulpotomy of human primary molars. J Microsc 2015; 260(3): 281-6.
[http://dx.doi.org/10.1111/jmi.12294] [PMID: 26258985]
[32] Lourenço Neto N, Marques NCT, Fernandes AP, *et al.* Clinical and radiographic evaluation of Portland cement added to radiopacifying agents in primary molar pulpotomies. Eur Arch Paediatr Dent 2015; 16(5): 377-82.
[http://dx.doi.org/10.1007/s40368-015-0177-9] [PMID: 25788172]
[33] Chakraborty A, Dey B, Dhar R, Sardar P. Healing of apical rarefaction of three nonvital open apex anterior teeth using a white portland cement apical plug. Contemp Clin Dent 2012; 3(6)(Suppl. 2): 177.
[http://dx.doi.org/10.4103/0976-237X.101101] [PMID: 23230357]
[34] De-Deus G, Coutinho-Filho T. The use of white Portland cement as an apical plug in a tooth with a necrotic pulp and wide-open apex: a case report. Int Endod J 2007; 40(8): 653-60.
[http://dx.doi.org/10.1111/j.1365-2591.2007.01269.x] [PMID: 17627699]
[35] Petrou MA, Alhamoui FA, Welk A, Altarabulsi MB, Alkilzy M, H Splieth C. A randomized clinical trial on the use of medical Portland cement, MTA and calcium hydroxide in indirect pulp treatment. Clin Oral Investig 2014; 18(5): 1383-9.
[http://dx.doi.org/10.1007/s00784-013-1107-z] [PMID: 24043482]
[36] Mahmoud O, Al-Meeri WA, Farook MS, Al-Afifi NA. Calcium Silicate-Based Cements as Root Canal Medicament. Clin Cosmet Investig Dent 2020; 12: 49-60.
[http://dx.doi.org/10.2147/CCIDE.S241015] [PMID: 32158275]
[37] Gandolfi MG, Silvia F, H PD, Gasparotto G, Carlo P. Calcium silicate coating derived from Portland cement as treatment for hypersensitive dentine. J Dent 2008; 36(8): 565-78.
[http://dx.doi.org/10.1016/j.jdent.2008.03.012] [PMID: 18538913]
[38] Gallego-Perez D, Higuita-Castro N, Quiroz FG, *et al.* Portland cement for bone tissue engineering: Effects of processing and metakaolin blends. J Biomed Mater Res B Appl Biomater 2011; 98B(2): 308-15.
[http://dx.doi.org/10.1002/jbm.b.31853] [PMID: 21648058]
[39] Dokami S, Raoofi S, Ashraf MJ, Khorshidi H. Histological analysis of the effect of accelerated portland cement as a bone graft substitute on experimentally-created three-walled intrabony defects in dogs. J Dent Res Dent Clin Dent Prospect 2007; 1(3): 131-5.
[PMID: 23277848]
[40] Campello RIC, Vasconcelos BCE, Sampaio GC, Rolim A, Porto GG. The use of Portland cement in the repair of mandibular fractures in rats. Acta Cir Bras 2011; 26(6): 426-32.
[http://dx.doi.org/10.1590/S0102-86502011000600004] [PMID: 22042103]
[41] Mansur AAP, Mansur HS. Preparation and characterization of 3D porous ceramic scaffolds based on portland cement for bone tissue engineering. J Mater Sci Mater Med 2009; 20(2): 497-505.
[http://dx.doi.org/10.1007/s10856-008-3612-1] [PMID: 18949538]
[42] Higuita-Castro N, Gallego-Perez D, Pelaez-Vargas A, *et al.* Reinforced Portland cement porous scaffolds for load-bearing bone tissue engineering applications. J Biomed Mater Res B Appl Biomater 2012; 100B(2): 501-7.
[http://dx.doi.org/10.1002/jbm.b.31976] [PMID: 22121151]
[43] Liu Y, Zhang Z, Jing R, Yan P. The interaction of sodium citrate and polycarboxylate-based superplasticizer on the rheological properties and viscoelasticity of cement-based materials. Constr Build Mater 2021; 293: 123466.
[http://dx.doi.org/10.1016/j.conbuildmat.2021.123466]
[44] Wynn-Jones G, Shelton RM, Hofmann MP. Injectable citrate□ modified Portland cement for use in vertebroplasty. J Biomed Mater Res B Appl Biomater 2014; 102(8): 1799-808.
[http://dx.doi.org/10.1002/jbm.b.33160] [PMID: 24711245]
[45] Möschner G, Lothenbach B, Figi R, Kretzschmar R. Influence of citric acid on the hydration of Portland cement. Cement Concr Res 2009; 39(4): 275-82.
[http://dx.doi.org/10.1016/j.cemconres.2009.01.005]
[46] Singh N, Prabha S, Singh A. Effect of lactic acid on the hydration of Portland cement. Cement concret Res 1986; 16(4): 545-53.
[http://dx.doi.org/10.1016/0008-8846(86)90092-X]
[47] Wynn-Jones G, Shelton RM, Hofmann MP. Development of Portland cement for orthopedic applications, establishing injectability and decreasing setting times. J Biomed Mater Res B Appl Biomater 2012; 100B(8): 2213-21.
[http://dx.doi.org/10.1002/jbm.b.32790] [PMID: 22887643]
[48] Gallego D, Higuita N, Garcia F, Ferrell N, Hansford DJ. Bioactive coatings on Portland cement substrates: Surface precipitation of apatite-like crystals. Mater Sci Eng C 2008; 28(3): 347-52.
[http://dx.doi.org/10.1016/j.msec.2007.04.020]
[49] Zaki DY. Investigation of the *in vitro* bioactivity of poly methyl methacrylate bone cement loaded with hydrated and anhydrous white Portland cement powder. Future Dental Journal 2018; 4(2): 99-104.
[http://dx.doi.org/10.1016/j.fdj.2018.11.001]
[50] Hamad BS. Investigations of chemical and physical properties of white cement concrete. Adv Cement Base Mater 1995; 2(4): 161-7.
[http://dx.doi.org/10.1016/1065-7355(95)90017-9]
[51] Islam I, Chng HK, Yap AUJ. X-ray diffraction analysis of mineral trioxide aggregate and Portland cement. Int Endod J 2006; 39(3): 220-5.
[http://dx.doi.org/10.1111/j.1365-2591.2006.01077.x] [PMID: 16507076]
[52] Moresova K, Skvara F. White cement: Properties, manufacture, prospects. Ceramics (Praha) 2001; 45(4): 158-63.
[53] Ahmed HMA, Luddin N, Kannan TP, Mokhtar KI, Ahmad A. Chemical analysis and biological properties of two different formulations of white portland cements. Scanning 2016; 38(4): 303-16.
[http://dx.doi.org/10.1002/sca.21270] [PMID: 26382064]
[54] Antonijević D, Ilić D, Medić V, Dodić S, Obradović-Djuriĉić K, Rakoĉević Z. Evaluation of conventional and digital radiography capacities for distinguishing dental materials on radiograms depending on the present radiopacifying agent. Vojnosanit Pregl 2014; 71(11): 1006-12.
[http://dx.doi.org/10.2298/VSP1411006A] [PMID: 25536802]
[55] Bosso-Martelo R, Guerreiro-Tanomaru JM, Viapiana R, Berbert FLC, Duarte MAH, Tanomaru-Filho M. Physicochemical properties of calcium silicate cements associated with microparticulate and nanoparticulate radiopacifiers. Clin Oral Investig 2016; 20(1): 83-90.
[http://dx.doi.org/10.1007/s00784-015-1483-7] [PMID: 25952552]
[56] Húngaro Duarte MA, de Oliveira El Kadre GD, Vivan RR, Guerreiro Tanomaru JM, Filho MT, de Moraes IG. Radiopacity of portland cement associated with different radiopacifying agents. J Endod 2009; 35(5): 737-40.
[http://dx.doi.org/10.1016/j.joen.2009.02.006] [PMID: 19410095]
[57] Guerreiro-Tanomaru JM, Cornélio ALG, Andolfatto C, Salles LP, Tanomaru-Filho M. pH and Antimicrobial Activity of Portland Cement Associated with Different Radiopacifying Agents. ISRN Dent 2012; 2012: 1-5.
[http://dx.doi.org/10.5402/2012/469019] [PMID: 23119173]
[58] Khalil I, Naaman A, Camilleri J. Investigation of a novel mechanically mixed mineral trioxide aggregate (MM-MTA ™). Int Endod J 2015; 48(8): 757-67.
[http://dx.doi.org/10.1111/iej.12373] [PMID: 25155985]
[59] Marciano MA, Garcia RB, Cavenago BC, *et al.* Influence of bismuth oxide concentration on the pH level and biocompatibility of white Portland cement. J Appl Oral Sci 2014; 22(4): 268-73.
[http://dx.doi.org/10.1590/1678-775720130059] [PMID: 25141197]
[60] Coutinho-Filho T, De-Deus G, Klein L, Manera G, Peixoto C, Gurgel-Filho ED. Radiopacity and histological assessment of Portland cement plus bismuth oxide. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2008; 106(6): e69-77.
[http://dx.doi.org/10.1016/j.tripleo.2008.07.028] [PMID: 18926734]
[61] Vivan RR, Ordinola-Zapata R, Bramante CM, *et al.* Evaluation of the radiopacity of some commercial and experimental root-end filling materials. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2009; 108(6): e35-8.
[http://dx.doi.org/10.1016/j.tripleo.2009.07.037] [PMID: 19913718]
[62] No S. 2000. https://webstore.ansi.org/Standards/ADA/ansiadaspecification572000
[63] Bueno CES, Zeferino EG, Manhães LRC Jr, Rocha DGP, Cunha RS, De Martin AS. Study of the bismuth oxide concentration required to provide Portland cement with adequate radiopacity for endodontic use. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2009; 107(1): e65-9.
[http://dx.doi.org/10.1016/j.tripleo.2008.09.016] [PMID: 19101486]
[64] Saghiri MA, Asatourian A, Rahmani B, Gutmann J, Morgano S. The pH and Bismuth Oxide Particle Size Can Affect Diametral Tensile

Strength of Mineral Trioxide Aggregate. Eur Endod J 2021; 2021: 1-8. [http://dx.doi.org/10.14744/eej.2021.27136] [PMID: 34047298]

[65] Li Q, Coleman NJ. Impact of Bi_2O_3 and ZrO_2 Radiopacifiers on the Early Hydration and C–S–H Gel Structure of White Portland Cement. J Funct Biomater 2019; 10(4): 46. [http://dx.doi.org/10.3390/jfb10040046] [PMID: 31635346]

[66] Hungaro Duarte MA, Minotti PG, Rodrigues CT, *et al.* Effect of different radiopacifying agents on the physicochemical properties of white Portland cement and white mineral trioxide aggregate. J Endod 2012; 38(3): 394-7. [http://dx.doi.org/10.1016/j.joen.2011.11.005] [PMID: 22341082]

[67] Antonijevic D, Medigovic I, Zrilic M, Jokic B, Vukovic Z, Todorovic L. The influence of different radiopacifying agents on the radiopacity, compressive strength, setting time, and porosity of Portland cement. Clinic Oral investigat 2014; 18(6): 1597-604. [http://dx.doi.org/10.1007/s00784-013-1130-0]

[68] Tanomaru-Filho M, Morales V, da Silva GF, *et al.* Compressive strength and setting time of MTA and portland cement associated with different radiopacifying agents. ISRN Dent 2012; 2012: 1-4. [http://dx.doi.org/10.5402/2012/898051] [PMID: 22957262]

[69] Coomaraswamy K, Lumley P, Hofmann M. Effect of bismuth oxide radioopacifier content on the material properties of an endodontic Portland cement-based (MTA-like) system. J Endod 2007; 33(3): 295-8. [http://dx.doi.org/10.1016/j.joen.2006.11.018] [PMID: 17320718]

[70] Saliba E, Abbassi-Ghadi S, Vowles R, Camilleri J, Hooper S, Camilleri J. Evaluation of the strength and radiopacity of Portland cement with varying additions of bismuth oxide. Int Endod J 2009; 42(4): 322-8. [http://dx.doi.org/10.1111/j.1365-2591.2008.01512.x] [PMID: 19220518]

[71] Weckwerth PH, Machado ACO, Kuga MC, Vivan RR, Polleto RS, Duarte MAH. Influence of radiopacifying agents on the solubility, pH and antimicrobial activity of portland cement. Braz Dent J 2012; 23(5): 515-20. [http://dx.doi.org/10.1590/S0103-64402012000500008] [PMID: 23306227]

[72] Vivan RR, Zapata RO, Zeferino MA, *et al.* Evaluation of the physical and chemical properties of two commercial and three experimental root-end filling materials. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2010; 110(2): 250-6. [http://dx.doi.org/10.1016/j.tripleo.2010.04.021] [PMID: 20659702]

[73] Formosa LM, Mallia B, Camilleri J. The effect of curing conditions on the physical properties of tricalcium silicate cement for use as a dental biomaterial. Int Endod J 2012; 45(4): 326-36. [http://dx.doi.org/10.1111/j.1365-2591.2011.01980.x] [PMID: 22044176]

[74] Silva GF, Bosso R, Ferino RV, *et al.* Microparticulated and nanoparticulated zirconium oxide added to calcium silicate cement: Evaluation of physicochemical and biological properties. J Biomed Mater Res A 2014; 102(12): n/a. [http://dx.doi.org/10.1002/jbm.a.35099] [PMID: 24497271]

[75] Camilleri J, Cutajar A, Mallia B. Hydration characteristics of zirconium oxide replaced Portland cement for use as a root-end filling material. Dent Mater 2011; 27(8): 845-54. [http://dx.doi.org/10.1016/j.dental.2011.04.011] [PMID: 21571360]

[76] Guerreiro-Tanomaru JM, Trindade-Junior A, Cesar Costa B, *et al.* Effect of zirconium oxide and zinc oxide nanoparticles on physicochemical properties and antibiofilm activity of a calcium silicate-based material. ScientificWorldJournal 2014; 2014: 1-6. [http://dx.doi.org/10.1155/2014/975213] [PMID: 25431798]

[77] Koutroulis A, Batchelor H, Kuehne SA, Cooper PR, Camilleri J. Investigation of the effect of the water to powder ratio on hydraulic cement properties. Dent Mater 2019; 35(8): 1146-54. [http://dx.doi.org/10.1016/j.dental.2019.05.011] [PMID: 31151852]

[78] Cutajar A, Mallia B, Abela S, Camilleri J. Replacement of radiopacifier in mineral trioxide aggregate; characterization and determination of physical properties. Dent Mater 2011; 27(9): 879-91. [http://dx.doi.org/10.1016/j.dental.2011.04.012] [PMID: 21571361]

[79] Li Q, Deacon AD, Coleman NJ. The impact of zirconium oxide nanoparticles on the hydration chemistry and biocompatibility of white Portland cement. Dent Mater J 2013; 32(5): 808-15. [http://dx.doi.org/10.4012/dmj.2013-113] [PMID: 24088838]

[80] Li Q, Coleman NJ. Hydration kinetics, ion-release and antimicrobial properties of white Portland cement blended with zirconium oxide nanoparticles. Dent Mater J 2014; 33(6): 805-10. [http://dx.doi.org/10.4012/dmj.2014-174] [PMID: 25427555]

[81] Antonijevic D, Jeschke A, Colovic B, *et al.* Addition of a fluoride-containing radiopacifier improves micromechanical and biological characteristics of modified calcium silicate cements. J Endod 2015; 41(12): 2050-7. [http://dx.doi.org/10.1016/j.joen.2015.09.008] [PMID: 26518217]

[82] Viapiana R, Guerreiro-Tanomaru JM, Hungaro-Duarte MA, Tanomaru-Filho M, Camilleri J. Chemical characterization and bioactivity of epoxy resin and Portland cement-based sealers with niobium and zirconium oxide radiopacifiers. Dent Mater 2014; 30(9): 1005-20. [http://dx.doi.org/10.1016/j.dental.2014.05.007] [PMID: 24950807]

[83] Tanomaru-Filho M, Nunes Reis JMS, Garcia AC, Bosso-Martelo R, Berbert FLCV, Guerreiro-Tanomaru J. Influence of addition of calcium oxide on physicochemical properties of Portland cement with zirconium or niobium oxide. J Conserv Dent 2015; 18(2): 105-8. [http://dx.doi.org/10.4103/0972-0707.153066] [PMID: 25829686]

[84] Silva GF, Tanomaru-Filho M, Bernardi MI, Guerreiro-Tanomaru JM, Cerri PS. Niobium pentoxide as radiopacifying agent of calcium silicate-based material: evaluation of physicochemical and biological properties. Clinic Oral investigat 2015; 19(8): 1-13. [http://dx.doi.org/10.1007/s00784-015-1412-9]

[85] Mestieri LB, Tanomaru-Filho M, Gomes-Cornélio AL, Salles LP, Bernardi MIB, Guerreiro-Tanomaru JM. Radiopacity and cytotoxicity of Portland cement associated with niobium oxide micro and nanoparticles. J Appl Oral Sci 2014; 22(6): 554-9. [http://dx.doi.org/10.1590/1678-775720140209] [PMID: 25591023]

[86] Viapiana R, Flumignan DL, Guerreiro-Tanomaru JM, Camilleri J, Tanomaru-Filho M. Physicochemical and mechanical properties of zirconium oxide and niobium oxide modified Portland cement-based experimental endodontic sealers. Int Endod J 2014; 47(5): 437-48. [http://dx.doi.org/10.1111/iej.12167] [PMID: 24033490]

[87] de SOUZA LC, Yadlapati M, Pereira Lopes H, Silva R, Letra A, Elias CN. Physico-chemical and Biological Properties of a New Portland Cement-based Root Repair Material. Eur Endod J 2017; 3(1): 38-47. [http://dx.doi.org/10.5152/eej.2017.17028] [PMID: 32161854]

[88] Lourenço Neto N, Marques NC, Fernandes AP, *et al.* Biocompatibility of Portland cement combined with different radiopacifying agents. J Oral Sci 2014; 56(1): 29-34. [http://dx.doi.org/10.2334/josnusd.56.29] [PMID: 24739705]

[89] Li Q, Deacon A, Coleman N. Iodoform-blended portland cement for dentistry. Prosthesis 2020; 2(4): 277-96. [http://dx.doi.org/10.3390/prosthesis2040025]

[90] Sabari MH, Kavitha M, Shobana S. Comparative evaluation of tissue response of MTA and portland cement with three radiopacifying agents: An animal study. J Contemp Dent Pract 2019; 20(1): 20-5. [http://dx.doi.org/10.5005/jp-journals-10024-2470] [PMID: 31058613]

[91] Camilleri J. Evaluation of the physical properties of an endodontic Portland cement incorporating alternative radiopacifiers used as root-end filling material. Int Endod J 2010; 43(3): 231-40. [http://dx.doi.org/10.1111/j.1365-2591.2009.01670.x] [PMID: 20158535]

[92] Gomes Cornélio AL, Salles LP, Campos da Paz M, Cirelli JA, Guerreiro-Tanomaru JM, Tanomaru Filho M. Cytotoxicity of Portland cement with different radiopacifying agents: a cell death study. J Endod 2011; 37(2): 203-10. [http://dx.doi.org/10.1016/j.joen.2010.11.017] [PMID: 21238803]

[93] Rahimi S, Salarinasab S, Ghasemi N, *et al. in vitro* induction of odontogenic activity of human dental pulp stem cells by white Portland cement enriched with zirconium oxide and zinc oxide components. J Dent Res Dent Clin Dent Prospect 2019; 13(1): 3-10. [http://dx.doi.org/10.15171/joddd.2019.001] [PMID: 31217912]

[94] Hwang YC, Lee SH, Hwang IN, *et al.* Chemical composition, radiopacity, and biocompatibility of Portland cement with bismuth oxide. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2009; 107(3): e96-e102. [http://dx.doi.org/10.1016/j.tripleo.2008.11.015] [PMID: 19157923]

[95] Zeferino EG, Bueno CES, Oyama LM, Ribeiro DA. Ex vivo assessment of genotoxicity and cytotoxicity in murine fibroblasts exposed to white MTA or white Portland cement with 15% bismuth oxide. Int Endod J 2010; 43(10): 843-8. [http://dx.doi.org/10.1111/j.1365-2591.2010.01747.x] [PMID: 20722754]

[96] Reyes-Carmona JF, Felippe MS, Felippe WT. Biomineralization ability and interaction of mineral trioxide aggregate and white portland cement with dentin in a phosphate-containing fluid. J Endod 2009; 35(5): 731-6. [http://dx.doi.org/10.1016/j.joen.2009.02.011] [PMID: 19410094]

[97] Chen C, Hsieh SC, Teng NC, *et al.* Radiopacity and cytotoxicity of Portland cement containing zirconia doped bismuth oxide radiopacifiers. J Endod 2014; 40(2): 251-4. [http://dx.doi.org/10.1016/j.joen.2013.07.006] [PMID: 24461413]

[98] Min KS, Lee SI, Lee Y, Kim EC. Effect of radiopaque Portland cement on mineralization in human dental pulp cells. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2009; 108(4): e82-6. [http://dx.doi.org/10.1016/j.tripleo.2009.05.022] [PMID: 19716724]

[99] Dreger LAS, Felippe WT, Reyes-Carmona JF, Felippe GS, Bortoluzzi EA, Felippe MCS. Mineral trioxide aggregate and Portland cement promote biomineralization *in vivo*. J Endod 2012; 38(3): 324-9. [http://dx.doi.org/10.1016/j.joen.2011.11.006] [PMID: 22341069]

[100] Abdullah D, Pitt Ford TR, Papaioannou S, Nicholson J, McDonald F. An evaluation of accelerated Portland cement as a restorative material. Biomaterials 2002; 23(19): 4001-10. [http://dx.doi.org/10.1016/S0142-9612(02)00147-3] [PMID: 12162333]

[101] Bortoluzzi EA, Broon NJ, Bramante CM, Garcia RB, de Moraes IG, Bernardineli N. Sealing ability of MTA and radiopaque Portland cement with or without calcium chloride for root-end filling. J Endod 2006; 32(9): 897-900. [http://dx.doi.org/10.1016/j.joen.2006.04.006] [PMID: 16934638]

[102] Reyes-Carmona JF, Felippe MS, Felippe WT. The biomineralization ability of mineral trioxide aggregate and Portland cement on dentin enhances the push-out strength. J Endod 2010; 36(2): 286-91. [http://dx.doi.org/10.1016/j.joen.2009.10.009] [PMID: 20113792]

[103] Bortoluzzi EA, Broon NJ, Bramante CM, Felippe WT, Tanomaru Filho M, Esberard RM. The influence of calcium chloride on the setting time, solubility, disintegration, and pH of mineral trioxide aggregate and white Portland cement with a radiopacifier. J Endod 2009; 35(4): 550-4. [http://dx.doi.org/10.1016/j.joen.2008.12.018] [PMID: 19345803]

[104] Wiltbank KB, Schwartz SA, Schindler WG. Effect of selected accelerants on the physical properties of mineral trioxide aggregate and Portland cement. J Endod 2007; 33(10): 1235-8. [http://dx.doi.org/10.1016/j.joen.2007.06.016] [PMID: 17889697]

[105] Antunesbortoluzzi E, Juárezbroon N, Antoniohungaroduarte M, Deoliveirademarchi A, Monteirobramante C. The use of a setting accelerator and its effect on pH and calcium ion release of mineral trioxide aggregate and white Portland cement. J Endod 2006; 32(12): 1194-7. [http://dx.doi.org/10.1016/j.joen.2006.07.018] [PMID: 17174682]

[106] Ong RM, Luddin N, Ahmed HMA, Omar NS. Cytotoxicity of accelerated white MTA and Malaysian white Portland cement on stem cells from human exfoliated deciduous teeth (SHED): An *in vitro* study. Singapore Dent J 2012; 33(1): 19-23. [http://dx.doi.org/10.1016/j.sdj.2012.11.001] [PMID: 23739319]

[107] Torkittikul P, Chaipanich A. Optimization of calcium chloride content on bioactivity and mechanical properties of white Portland cement. Mater Sci Eng C 2012; 32(2): 282-9. [http://dx.doi.org/10.1016/j.msec.2011.10.030]

[108] Dalla PT, Tragazikis IK, Trakakis G, Galiotis C, Dassios KG, Matikas TE. Multifunctional Cement Mortars Enhanced with Graphene Nanoplatelets and Carbon Nanotubes. Sensors (Basel) 2021; 21(3): 933. [http://dx.doi.org/10.3390/s21030933] [PMID: 33573281]

[109] Akono AT. Fracture toughness of one- and two-dimensional nanoreinforced cement *via* scratch testing. Philosoph transact Series A Mathemat Physical. Eng Sci 2021; 379(2203): 20200288.

[110] Li W, Li X, Chen SJ, Liu YM, Duan WH, Shah SP. Effects of graphene oxide on early-age hydration and electrical resistivity of Portland cement paste. Constr Build Mater 2017; 136: 506-14. [http://dx.doi.org/10.1016/j.conbuildmat.2017.01.066]

[111] Wang L, Zhang S, Zheng D, *et al.* Effect of graphene oxide (GO) on the morphology and microstructure of cement hydration products. Nanomaterials (Basel) 2017; 7(12): 429-38. [http://dx.doi.org/10.3390/nano7120429] [PMID: 29206157]

[112] Yang H, Monasterio M, Cui H, Han N. Experimental study of the effects of graphene oxide on microstructure and properties of cement paste composite. Compos, Part A Appl Sci Manuf 2017; 102: 263-72. [http://dx.doi.org/10.1016/j.compositesa.2017.07.022]

[113] Du S, Tang Z, Zhong J, Ge Y, Shi X. Effect of admixing graphene oxide on abrasion resistance of ordinary portland cement concrete. AIP Adv 2019; 9(10): 105110. [http://dx.doi.org/10.1063/1.5124388]

[114] Gong K, Pan Z, Korayem AH, *et al.* Reinforcing effects of graphene oxide on portland cement paste. J Mater Civ Eng 2015; 27(2): A4014010. [http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001125]

[115] Lv S, Ting S, Liu J, Zhou Q. Use of graphene oxide nanosheets to regulate the microstructure of hardened cement paste to increase its strength and toughness. CrystEngComm 2014; 16(36): 8508-16. [http://dx.doi.org/10.1039/C4CE00684D]

[116] Dubey N, Rajan SS, Bello YD, Min KS, Rosa V. Graphene nanosheets to improve physico-mechanical properties of bioactive calcium silicate cements. Materials (Basel) 2017; 10(6): 606-9. [http://dx.doi.org/10.3390/ma10060606] [PMID: 28772959]

[117] Mehrali M, Moghaddam E, Seyed Shirazi SF, *et al.* Mechanical and *in vitro* biological performance of graphene nanoplatelets reinforced calcium silicate composite. PLoS One 2014; 9(9): e106802. [http://dx.doi.org/10.1371/journal.pone.0106802] [PMID: 25229540]

[118] Qutieshat A, Al-Hiyasat A, Islam M. The effect of adding graphene oxide nanoplatelets to Portland cement: Potential for dental applications. J Conserv Dent 2020; 23(1): 15-20. [http://dx.doi.org/10.4103/JCD.JCD_274_20] [PMID: 33223635]

[119] Raki L, Beaudoin J, Alizadeh R, Makar J, Sato T. Cement and concrete nanoscience and nanotechnology. Materials (Basel) 2010; 3(2): 918-42. [http://dx.doi.org/10.3390/ma3020918]

[120] Abu Al-Rub RK, Ashour AI, Tyson BM. On the aspect ratio effect of multi-walled carbon nanotube reinforcements on the mechanical properties of cementitious nanocomposites. Constr Build Mater 2012; 35: 647-55. [http://dx.doi.org/10.1016/j.conbuildmat.2012.04.086]

[121] Wang B, Han Y, Zhang T. Morphological properties of surface-treated carbon nanotubes in cement-based composites. J Nanosci Nanotechnol 2012; 12(11): 8415-9. [http://dx.doi.org/10.1166/jnn.2012.6635] [PMID: 23421224]

[122] Konsta-Gdoutos MS, Metaxa ZS, Shah SP. Highly dispersed carbon nanotube reinforced cement based materials. Cement Concr Res 2010; 40(7): 1052-9. [http://dx.doi.org/10.1016/j.cemconres.2010.02.015]

[123] Manzur T, Yazdani N, Emon MAB. Effect of carbon nanotube size on compressive strengths of nanotube reinforced cementitious composites. J Mater 2014; 2014: 1-8. [http://dx.doi.org/10.1155/2014/960984]

[124] Kumar S, Kolay P, Malla S, Mishra S. Effect of multiwalled carbon nanotubes on mechanical strength of cement paste. J Mater Civ Eng 2012; 24(1): 84-91. [http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000350]

[125] Metaxa ZS, Seo JWT, Konsta-Gdoutos MS, Hersam MC, Shah SP. Highly concentrated carbon nanotube admixture for nano-fiber reinforced cementitious materials. Cement Concr Compos 2012; 34(5): 612-7. [http://dx.doi.org/10.1016/j.cemconcomp.2012.01.006]

[126] Siddique R, Mehta A. Effect of carbon nanotubes on properties of cement mortars. Constr Build Mater 2014; 50: 116-29. [http://dx.doi.org/10.1016/j.conbuildmat.2013.09.019]

[127] Sobolev K, Flores I, Hermosillo R, Torres-Martínez LM. Nanomaterials and nanotechnology for high-performance cement composites. Recent Develop Future Perspect 2006; 91: 118-23.

[128] Ma C, He J, Qin T, Long G, Du Y, Xie Y. A comparison of the influence of micro- and nano-silica on hydration kinetics of Portland cement under different temperatures. Constr Build Mater 2020; 248: 118670. [http://dx.doi.org/10.1016/j.conbuildmat.2020.118670]

[129] Land G, Stephan D. The influence of nano-silica on the hydration of ordinary Portland cement. J Mater Sci 2012; 47(2): 1011-7. [http://dx.doi.org/10.1007/s10853-011-5881-1]

[130] Zheng D, Monasterio M, Feng W, Tang W, Cui H, Dong Z. Hydration Characteristics of Tricalcium Aluminate in the Presence of Nano-Silica. Nanomaterials (Basel) 2021; 11(1): 199-10. [http://dx.doi.org/10.3390/nano11010199] [PMID: 33466793]

[131] Singh LP, Karade SR, Bhattacharyya SK, Yousuf MM, Ahalawat S. Beneficial role of nanosilica in cement based materials – A review. Constr Build Mater 2013; 47: 1069-77. [http://dx.doi.org/10.1016/j.conbuildmat.2013.05.052]

[132] Tobón JI, Payá JJ, Borrachero MV, Restrepo OJ. Mineralogical evolution of Portland cement blended with silica nanoparticles and its effect on mechanical strength. Constr Build Mater 2012; 36: 736-42. [http://dx.doi.org/10.1016/j.conbuildmat.2012.06.043]

[133] Hussain ST, Sastry K. Study of strength properties of concrete by using micro silica and nano silica. Int J Res Eng Technol 2014; 3(10): 103-8.

[http://dx.doi.org/10.15623/ijret.2014.0310016]

[134] Shih JY, Chang TP, Hsiao TC. Effect of nanosilica on characterization of Portland cement composite. Mater Sci Eng A 2006; 424(1-2): 266-74.
[http://dx.doi.org/10.1016/j.msea.2006.03.010]

[135] Akbari M, Zebarjad SM, Nategh B, Rouhani A. Effect of nano silica on setting time and physical properties of mineral trioxide aggregate. J Endod 2013; 39(11): 1448-51.
[http://dx.doi.org/10.1016/j.joen.2013.06.035] [PMID: 24139272]

[136] Beheri HH, Mohamed KR, El-Bassyouni GT. Mechanical and microstructure of reinforced hydroxyapatite/calcium silicate nano-composites materials. Mater Des 2013; 44: 461-8.
[http://dx.doi.org/10.1016/j.matdes.2012.08.020]

[137] Petrović V, Opačić-Galić V, Živković S, *et al.* Biocompatibility of new nanostructural materials based on active silicate systems and hydroxyapatite: *in vitro* and *in vivo* study. Int Endod J 2015; 48(10): 966-75.
[http://dx.doi.org/10.1111/iej.12391] [PMID: 25288256]

[138] Liu WC, Wang HY, Chen LC, Huang SW, Wu C, Chung RJ. Hydroxyapatite/tricalcium silicate composites cement derived from novel two-step sol-gel process with good biocompatibility and applications as bone cement and potential coating materials. Ceram Int 2019; 45(5): 5668-79.
[http://dx.doi.org/10.1016/j.ceramint.2018.12.032]

[139] Opačić-Galić V, Petrović V, Živković S, *et al.* New nanostructural biomaterials based on active silicate systems and hydroxyapatite: characterization and genotoxicity in human peripheral blood lymphocytes. Int Endod J 2013; 46(6): 506-16.
[http://dx.doi.org/10.1111/iej.12017] [PMID: 23173688]

[140] Taptimdee W, Chindaprasirt P, Otsuka Y, Mutoh Y, Laonapakul T. Strength and Bioactivity of Hydroxyapatite/White Portland Cement (HAp/WPC) under Simulated Body Fluid (SBF) Solution. Mater Sci 2020; 2020: 1-10.

[141] Dasgupta S, Tarafder S, Bandyopadhyay A, Bose SJMS. Effect of grain size on mechanical, surface and biological properties of microwave sintered hydroxyapatite. Material 2013; 33(5): 2846-54.

[142] Guerreiro-Tanomaru JM, Vázquez-García FA, Bosso-Martelo R, Bernardi MIB, Faria G, Tanomaru Filho M. Effect of addition of nano-hydroxyapatite on physico-chemical and antibiofilm properties of calcium silicate cements. J Appl Oral Sci 2016; 24(3): 204-10.
[http://dx.doi.org/10.1590/1678-775720150422] [PMID: 27383700]

[143] Cao M, Ming X, He K, Li L, Shen S. Effect of macro-, micro-and nano-calcium carbonate on properties of cementitious composites—A review. Materials (Basel) 2019; 12(5): 781-90.
[http://dx.doi.org/10.3390/ma12050781] [PMID: 30866439]

[144] Wang Y, He F, Wang J, Hu Q. Comparison of Effects of Sodium Bicarbonate and Sodium Carbonate on the Hydration and Properties of Portland Cement Paste. Materials (Basel) 2019; 12(7): 1033.
[http://dx.doi.org/10.3390/ma12071033] [PMID: 30925790]

[145] Camiletti J, Soliman AM, Nehdi ML. Effect of nano-calcium carbonate on early-age properties of ultra-high-performance concrete. Mag Concr Res 2013; 65(5): 297-307.
[http://dx.doi.org/10.1680/macr.12.00015]

[146] Poudyal L, Adhikari K, Won M. Mechanical and durability properties of portland limestone cement (PLC) incorporated with nano calcium carbonate (CaCO3). Materials (Basel) 2021; 14(4): 905-10.
[http://dx.doi.org/10.3390/ma14040905] [PMID: 33672851]

[147] Liu X, Chen L, Liu A, Wang X. Effect of nano-CaCO3 on properties of cement paste. En Proced 2012; 16: 991-6.
[http://dx.doi.org/10.1016/j.egypro.2012.01.158]

[148] Wang Y, He F, Wang J, Wang C, Xiong Z. Effects of calcium bicarbonate on the properties of ordinary Portland cement paste. Constr Build Mater 2019; 225: 591-600.
[http://dx.doi.org/10.1016/j.conbuildmat.2019.07.262]

[149] Arandi NZ, Rabi T. TheraCal LC: from biochemical and bioactive properties to clinical applications. Int J Dent 2018; 2018: 1-6.
[http://dx.doi.org/10.1155/2018/3484653] [PMID: 29785184]

[150] Kunert M, Lukomska-Szymanska M. Bio-inductive materials in direct and indirect pulp capping-a review article. Material 2020; 13(5): 1-13.
[http://dx.doi.org/10.3390/ma13051204]

[151] Gandolfi MG, Siboni F, Prati C. Chemical-physical properties of TheraCal, a novel light-curable MTA-like material for pulp capping. Int Endod J 2012; 45(6): 571-9.
[http://dx.doi.org/10.1111/j.1365-2591.2012.02013.x] [PMID: 22469093]

[152] Camilleri J. Hydration characteristics of Biodentine and Theracal used as pulp capping materials. Dent Mater 2014; 30(7): 709-15.
[http://dx.doi.org/10.1016/j.dental.2014.03.012] [PMID: 24793199]

[153] Lee BN, Lee BG, Chang HS, Hwang YC, Hwang IN, Oh WM. Effects of a novel light-curable material on odontoblastic differentiation of human dental pulp cells. Int Endod J 2017; 50(5): 464-71.
[http://dx.doi.org/10.1111/iej.12642] [PMID: 27015645]

[154] Gasperi TL, Silveira JAC, Schmidt TF, Teixeira CS, Garcia LFR, Bortoluzzi EA. Physical-mechanical properties of a resin-modified calcium silicate material for pulp capping. Braz Dent J 2020; 31(3): 252-6.
[http://dx.doi.org/10.1590/0103-6440202003079] [PMID: 32667514]

[155] Cengiz E, Ulusoy N. Microshear bond strength of tri-calcium silicate-based cements to different restorative materials. J Adhes Dent 2016; 18(3): 231-7.
[PMID: 27045140]

[156] Karadas M, Cantekin K, Gumus H, Ateş SM, Duymuş ZY. Evaluation of the bond strength of different adhesive agents to a resin-modified calcium silicate material (TheraCal LC). Scanning 2016; 38(5): 403-11.
[http://dx.doi.org/10.1002/sca.21284] [PMID: 26553783]

[157] Kim Y, Lee D, Song D, Kim HM, Kim SY. Biocompatibility and bioactivity of set direct pulp capping materials on human dental pulp stem cells. Materials 2020; 13(18): 3925.
[http://dx.doi.org/10.3390/ma13183925] [PMID: 32899877]

[158] Jeanneau C, Laurent P, Rombouts C, Giraud T, About I. Light-cured tricalcium silicate toxicity to the dental pulp. J Endod 2017; 43(12): 2074-80.
[http://dx.doi.org/10.1016/j.joen.2017.07.010] [PMID: 29032813]

[159] Rodríguez-Lozano FJ, López-García S, García-Bernal D, *et al.* Cytocompatibility and bioactive properties of the new dual-curing resin-modified calcium silicate-based material for vital pulp therapy. Clin Oral Investig 2021; 25(8): 5009-24.
[http://dx.doi.org/10.1007/s00784-021-03811-0] [PMID: 33638052]

[160] Li X, De Munck J, Van Landuyt K, Pedano M, Chen Z, Van Meerbeek B. How effectively do hydraulic calcium-silicate cements re-mineralize demineralized dentin. Dent Mater 2017; 33(4): 434-45.
[http://dx.doi.org/10.1016/j.dental.2017.01.015] [PMID: 28233602]

[161] Çelik N, Işcan Yapar M, Taghizadehghalehjoughi A, Nalcı KA. Influence of resveratrol application with pulp□capping materials on the genetic expression levels of stem cells. Int Endod J 2020; 53(9): 1253-63.
[http://dx.doi.org/10.1111/iej.13345] [PMID: 32515014]

[162] Zhang Y, Chen Y, Hu Y, Huang F, Xiao Y. Quaternary ammonium compounds in dental restorative materials. Dent Mater J 2018; 37(2): 183-91.
[http://dx.doi.org/10.4012/dmj.2017-096] [PMID: 29225280]

[163] Yang Y, Huang L, Dong Y, *et al. in vitro* antibacterial activity of a novel resin-based pulp capping material containing the quaternary ammonium salt MAE-DB and Portland cement. PLoS One 2014; 9(11): e112549.
[http://dx.doi.org/10.1371/journal.pone.0112549] [PMID: 25389975]

[164] Yang YW, Yu F, Zhang HC, *et al.* Physicochemical properties and cytotoxicity of an experimental resin-based pulp capping material containing the quaternary ammonium salt and Portland cement. Int Endod J 2018; 51(1): 26-40.
[http://dx.doi.org/10.1111/iej.12777] [PMID: 28375561]

[165] Yu F, Dong Y, Yang Y, *et al.* Effect of an experimental direct pulp-capping material on the properties and osteogenic differentiation of human dental pulp stem cells. Sci Rep 2016; 6(1): 34713.
[http://dx.doi.org/10.1038/srep34713] [PMID: 27698421]

[166] Flatt R, Schober I. Superplasticizers and the rheology of concrete Understanding the rheology of concrete. Elsevier 2012; pp. 144-208.
[http://dx.doi.org/10.1533/9780857095282.2.144]

[167] Sha S, Wang M, Shi C, Xiao Y. Influence of the structures of polycarboxylate superplasticizer on its performance in cement-based materials-A review. Constr Build Mater 2020; 233: 117257.
[http://dx.doi.org/10.1016/j.conbuildmat.2019.117257]

[168] Wongkornchaowalit N, Lertchirakarn V. Setting time and flowability of accelerated Portland cement mixed with polycarboxylate superplasticizer. J Endod 2011; 37(3): 387-9.
[http://dx.doi.org/10.1016/j.joen.2010.11.039] [PMID: 21329827]

[169] Kong X, Zhang Y, Hou S. Study on the rheological properties of Portland cement pastes with polycarboxylate superplasticizers. Rheol Acta 2013; 52(7): 707-18.
[http://dx.doi.org/10.1007/s00397-013-0713-7]

[170] Panahi F, Rabiee SM, Shidpour R. Synergic effect of chitosan and dicalcium phosphate on tricalcium silicate-based nanocomposite for root-end dental application. Mater Sci Eng C 2017; 80: 631-41.

[http://dx.doi.org/10.1016/j.msec.2017.07.012] [PMID: 28866210]
[171] Lasheras-Zubiate M, Navarro-Blasco I, Fernández JM, Álvarez JI. Effect of the addition of chitosan ethers on the fresh state properties of cement mortars. Cement Concr Compos 2012; 34(8): 964-73. [http://dx.doi.org/10.1016/j.cemconcomp.2012.04.010]
[172] Subhi H, Husein A, Mohamad D, Nurul AA. Physicochemical, mechanical and cytotoxicity evaluation of chitosan-based accelerated portland cement. J Mater Res Technol 2020; 9(5): 11574-86. [http://dx.doi.org/10.1016/j.jmrt.2020.07.108]
[173] Lasheras-Zubiate M, Navarro-Blasco I, Fernández JM, Alvarez JI. Studies on chitosan as an admixture for cement-based materials: Assessment of its viscosity enhancing effect and complexing ability for heavy metals. J Appl Polym Sci 2011; 120(1): 242-52. [http://dx.doi.org/10.1002/app.33048]
[174] Lin Q, Lan X, Li Y, *et al.* Anti-washout carboxymethyl chitosan modified tricalcium silicate bone cement: preparation, mechanical properties and *in vitro* bioactivity. J Mater Sci Mater Med 2010; 21(12): 3065-76. [http://dx.doi.org/10.1007/s10856-010-4160-z] [PMID: 20890641]
[175] Kamali A, Javadpour S, Javid B, Kianvash Rad N, Naddaf Dezfuli S. Effects of chitosan and zirconia on setting time, mechanical strength, and bioactivity of calcium silicate-based cement. Int J Appl Ceram Technol 2017; 14(2): 135-44. [http://dx.doi.org/10.1111/ijac.12636]
[176] Mahmood A, Noman MT, Pechočiaková M, *et al.* Geopolymers and fiber-reinforced concrete composites in civil engineering. Polymers 2021; 13(13): 2099. [http://dx.doi.org/10.3390/polym13132099] [PMID: 34202211]
[177] Tippayasam C, Sutikulsombat S, Kamseu E, *et al.* In vitro surface reaction in SBF of a non-crystalline aluminosilicate (geopolymer) material. J Australian Ceramic Soc 2019; 55(1): 11-7. [http://dx.doi.org/10.1007/s41779-018-0205-4]
[178] Sayed M, Gado RA, Naga SM, Colombo P, Elsayed H. Influence of the thermal treatment on the characteristics of porous geopolymers as potential biomaterials. Mater Sci Eng C 2020; 116: 111171. [http://dx.doi.org/10.1016/j.msec.2020.111171] [PMID: 32806273]
[179] Pangdaeng S, Sata V, Aguiar JB, Pacheco-Torgal F, Chindaprasirt P. Apatite formation on calcined kaolin–white Portland cement geopolymer. Mater Sci Eng C 2015; 51: 1-6. [http://dx.doi.org/10.1016/j.msec.2015.02.039] [PMID: 25842101]
[180] Pangdaeng S, Sata V, Chindaprasirt P. Effect of sodium hydroxide concentration and sodium silicate to sodium hydroxide ratio on properties of calcined kaolin-white portland cement geopolymer. Int J 2018; 14(46): 121-8.
[181] Bortoluzzi EA, Silveira Teixeira C, Broon NJ, *et al.* Tissue response to white mineral aggregate-based cement containing barium sulfate as alternative radiopacifier: A randomized controlled animal study. Microsc Res Tech 2021; 84(4): 705-11. [http://dx.doi.org/10.1002/jemt.23629] [PMID: 33089621]
[182] Mestieri LB, Gomes-Cornélio AL, Rodrigues EM, Faria G, Guerreiro-Tanomaru JM, Tanomaru-Filho M. Cytotoxicity and bioactivity of calcium silicate cements combined with niobium oxide in different cell lines. Braz Dent J 2017; 28(1): 65-71. [http://dx.doi.org/10.1590/0103-6440201700525] [PMID: 28301020]
[183] Flores-Ledesma A, Barceló Santana F, Bucio L, Arenas-Alatorre JA, Faraji M, Wintergerst AM. Bioactive materials improve some physical properties of a MTA-like cement. Mater Sci Eng C 2017; 71: 150-5. [http://dx.doi.org/10.1016/j.msec.2016.09.079] [PMID: 27987692]
[184] Vazquez-Garcia F, Tanomaru-Filho M, Chávez-Andrade GM, Bosso-Martelo R, Basso-Bernardi MI, Guerreiro-Tanomaru JM. Effect of silver nanoparticles on physicochemical and antibacterial properties of calcium silicate cements. Braz Dent J 2016; 27(5): 508-14. [http://dx.doi.org/10.1590/0103-6440201600689] [PMID: 27982226]
[185] Slompo C, Peres-Buzalaf C, Gasque KCS, *et al.* Experimental Calcium Silicate-Based Cement with and without Zirconium Oxide Modulates Fibroblasts Viability. Braz Dent J 2015; 26(6): 587-91. [http://dx.doi.org/10.1590/0103-6440201300316] [PMID: 26963200]
[186] Marciano MA, Costa RM, Camilleri J, Mondelli RFL, Guimarães BM, Duarte MAH. Assessment of color stability of white mineral trioxide aggregate angelus and bismuth oxide in contact with tooth structure. J Endod 2014; 40(8): 1235-40. [http://dx.doi.org/10.1016/j.joen.2014.01.044] [PMID: 25069940]
[187] Viapiana R, Guerreiro-Tanomaru J, Tanomaru-Filho M, Camilleri J. Interface of dentine to root canal sealers. J Dent 2014; 42(3): 336-50. [http://dx.doi.org/10.1016/j.jdent.2013.11.013] [PMID: 24287256]
[188] Coleman NJ, Li Q. The impact of zirconium oxide radiopacifier on the early hydration behaviour of white Portland cement. Mater Sci Eng C 2013; 33(1): 427-33. [http://dx.doi.org/10.1016/j.msec.2012.09.009] [PMID: 25428091]
[189] Bortoluzzi EA, Guerreiro-Tanomaru JM, Tanomaru-Filho M, Duarte MAH. Radiographic effect of different radiopacifiers on a potential retrograde filling material. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2009; 108(4): 628-32. [http://dx.doi.org/10.1016/j.tripleo.2009.04.044] [PMID: 19699115]
[190] Kim EC, Lee BC, Chang HS, Lee W, Hong CU, Min KS. Evaluation of the radiopacity and cytotoxicity of Portland cements containing bismuth oxide. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2008; 105(1): e54-7. [http://dx.doi.org/10.1016/j.tripleo.2007.08.001] [PMID: 18155604]
[191] Bakhtiar H, Nekoofar MH, Aminishakib P, *et al.* Human pulp responses to partial pulpotomy treatment with theracal as compared with biodentine and proroot MTA: A clinical trial. J Endod 2017; 43(11): 1786-91. [http://dx.doi.org/10.1016/j.joen.2017.06.025] [PMID: 28822566]
[192] Gurcan AT, Seymen F. Clinical and radiographic evaluation of indirect pulp capping with three different materials: a 2-year follow-up study. Eur J Paediatr Dent 2019; 20(2): 105-10. [PMID: 31246084]
[193] Erfanparast L, Iranparvar P, Vafaei A. Direct pulp capping in primary molars using a resin-modified Portland cement-based material (TheraCal) compared to MTA with 12-month follow-up: a randomised clinical trial. European archives of paediatric dentistry : official journal of the European Academy Paediatric Dent 2018; 19(3): 197-203.
[194] Cengiz E, Yilmaz HG. Efficacy of erbium, chromium-doped:yttrium, scandium, gallium, and garnet laser irradiation combined with resin-based tricalcium silicate and calcium hydroxide on direct pulp capping: A randomized clinical trial. J Endod 2016; 42(3): 351-5. [http://dx.doi.org/10.1016/j.joen.2015.11.015] [PMID: 26723484]
[195] Varma BR, Menon NP, Janardhanan S, Kumaran P, Xavier A, Govinda B. Clinical and radiographic comparison of indirect pulp treatment using light-cured calcium silicate and mineral trioxide aggregate in primary molars: A randomized clinical trial. Contemp Clin Dent 2016; 7(4): 475-80. [http://dx.doi.org/10.4103/0976-237X.194109] [PMID: 27994414]
[196] Alqahtani AR, Yaman P, McDonald N, Dennison J. Efficacy of calcium hydroxide and resin-modified calcium silicate as pulp-capping materials: a retrospective study. Gen Dent 2020; 68(6): 50-4. [PMID: 33136046]
[197] Peskersoy C, Lukarcanin J, Turkun M. Efficacy of different calcium silicate materials as pulp-capping agents: Randomized clinical trial. J Dent Sci 2021; 16(2): 723-31. [http://dx.doi.org/10.1016/j.jds.2020.08.016] [PMID: 33854725]
[198] Sahin N, Saygili S, Akcay M. Clinical, radiographic, and histological evaluation of three different pulp-capping materials in indirect pulp treatment of primary teeth: a randomized clinical trial. Clin Oral Investig 2021; 25(6): 3945-55. [http://dx.doi.org/10.1007/s00784-020-03724-4] [PMID: 33404764]
[199] Cannon M, Gerodias N, Vieira A, Percinoto C, Jurado R. Primate pulpal healing after exposure and TheraCal application. J Clin Pediatr Dent 2014; 38(4): 333-7. [http://dx.doi.org/10.17796/jcpd.38.4.m585322121536q71] [PMID: 25571685]
[200] Lee H, Shin Y, Kim SO, Lee HS, Choi HJ, Song JS. Comparative Study of Pulpal Responses to Pulpotomy with ProRoot MTA, RetroMTA, and TheraCal in Dogs' Teeth. J Endod 2015; 41(8): 1317-24. [http://dx.doi.org/10.1016/j.joen.2015.04.007] [PMID: 26015158]
[201] Li X, Pedano MS, Camargo B, *et al.* Experimental tricalcium silicate cement induces reparative dentinogenesis. Dent Mater 2018; 34(9): 1410-23. [http://dx.doi.org/10.1016/j.dental.2018.06.016] [PMID: 29941352]
[202] Hinata G, Yoshiba K, Han L, Edanami N, Yoshiba N, Okiji T. Bioactivity and biomineralization ability of calcium silicate-based pulp-capping materials after subcutaneous implantation. Int Endod J 2017; 50(Suppl. 2): e40-51. [http://dx.doi.org/10.1111/iej.12802] [PMID: 28649791]