



ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.intl.elsevierhealth.com/journals/dema

Bonding to caries affected dentine

Naghmeh Meraji^a, Mohammad H. Nekoofar^{a,b}, Kazem Ashofteh Yazdi^a,
 Mohammad Reza Sharifian^a, Noushin Fakhari^c, Josette Camilleri^{d,e,*}

^a Department of Endodontics, School of Dentistry, Tehran University of Medical Sciences, Tehran, Iran,

^b Endodontology Research Group, School of Dentistry, Cardiff University, Cardiff, Wales, UK,

^c Department of Endodontics, School of Dentistry, Shahid Sadughi University of Medical Sciences, Yazd, Iran

^d Department of Restorative Dentistry, Faculty of Dental Surgery, University of Malta, Msida, Malta,

^e School of Dentistry, Institute of Clinical Sciences, College of Clinical and Medical Sciences, University of Birmingham, Edgbaston, Birmingham, UK

ARTICLE INFO

Article history:

Received 1 March 2018

Received in revised form

29 April 2018

Accepted 21 May 2018

Available online xxx

Keywords:

Caries

Characterization

Dentine replacement materials

Shear bond strength

Demineralized dentine

Remineralization

ABSTRACT

Objectives. Dentine replacement materials are often placed over caries affected dentine (CAD). The aim of this study was to compare the bonding characteristics and interactions of selected hydraulic calcium silicate-based dentine replacement materials to CAD and sound dentine.

Methods. Three hydraulic calcium silicate-based dentine replacement materials were assessed: Retro MTA, Biodentine and Theracal LC. Material characterization was done by scanning electron microscopy and X-ray diffraction analyses. Blocks of sound and CAD were prepared and standardized by Vickers microhardness testing. Half of the affected and sound dentine blocks were pretreated with 5.25% NaOCl prior to material placement. The materials were stored either for 1 week or 24 weeks in 37 °C in fully saturated conditions. Shear bond strength was assessed at both time periods. Radiopacity of the interfacial dentine was also evaluated to assess the remineralization potential of the dentine replacement materials.

Results. The reaction of Theracal was slower than that of the water-based materials. The bond strengths of different materials did not differ after 1 week ($P > 0.05$). The bond strength of Biodentine and Retro MTA increased over time but no change was observed for Theracal. NaOCl pre-treatment deteriorated the bond strength to sound dentine but improvement was observed in affected dentine. Radiopacity changes were observed after 24 weeks.

Significance. Biodentine and Retro MTA showed better bonding to CAD. Pretreatment with NaOCl improved the bond strength of dentine replacement materials to CAD.

© 2018 The Academy of Dental Materials. Published by Elsevier Inc. All rights reserved.

1. Introduction

Carious dentin consists of two distinct layers: an outer bacterially infected layer of dentine, and an inner layer of affected

dentine [1]. The caries-infected layer (CID) is highly demineralized, physiologically unremineralizable and contains irreversibly denatured collagen fibrils with a virtual disappearance of cross-linkages [2,3]. On the other hand, the caries-affected layer (CAD) is uninfected, partially deminer-

* Corresponding author at: School of Dentistry, Institute of Clinical Sciences, College of Medical and Dental Sciences, The University of Birmingham, 5 Mill Pool Way, Edgbaston, Birmingham, B5 7EG, UK.

E-mail address: J.Camilleri@bham.ac.uk (J. Camilleri).

<https://doi.org/10.1016/j.dental.2018.05.017>

10109-5641/© 2018 The Academy of Dental Materials. Published by Elsevier Inc. All rights reserved.

alized and physiologically remineralizable [2–4]. High porosity and exposure of collagen fibers along with a decrease in the surface energy are seen in the inter-tubular CAD [2–4]. Collagen cross-linking remains intact which can function as a scaffold for remineralization of intertubular dentine [2–4]. Therefore, the caries-affected layer should be preserved during clinical treatments.

It has been shown that CAD exhibits lower bond strengths to restorative materials such as glass ionomer and composite resins than sound dentine [5,6]. The change in chemical and morphological characteristics of CAD may be a reason for this lower bond strength. As CAD is partially demineralized, an irregular and thicker hybrid layer enriched with organic components is created on it [7–9].

In an attempt to improve bond strength to CAD, studies have suggested pretreatment of dentine with sodium hypochlorite solution (NaOCl) [8]. NaOCl can effectively dissolve organic components. Taniguchi et al. [8] demonstrated that pretreatment with 6% NaOCl for 15 s could significantly improve the bond strengths of both 1-step and 2-step self-etch system to CAD. This finding was attributed to the dissolution of superficial organic components of smear layer by NaOCl.

When treating deep carious lesions, the dentine replacement materials come in contact with CAD. Hydraulic calcium silicate cements have shown a lot of promise as dentine replacements due to their beneficial effect on the pulp. Biodentine (Septodont, Saint Maur des Fosses, France) [10] and Retro MTA (BioMTA, Seoul, Korea) [11] are fast setting dentine replacement materials exhibiting clinically suitable properties. Theracal LC (Bisco, Schaumburg, IL, USA) is a resin-modified light curable dentine replacement material used as a liner under composite restorations [12]. It contains a special hydrophilic resin matrix, which allows water penetration and ion release, resulting in apatite formation and sealing of the tooth [13]. The Biodentine and Retro MTA are water-based and composed mostly of tricalcium silicate cement. The Theracal is resin based and contains fillers and other additives. Although previous research has reported the apatite formation and the ion release in solution [13], the calcium ion releasing ability and hydration of the tricalcium silicate component of the Theracal is disputed [14,15]. This will affect the material clinical performance.

Most research on the interactions between hydraulic calcium silicate-based dentine replacement materials and dentine is performed using sound dentine [16,17]. Clinically, when used over the pulp, these material are rarely placed on sound dentine. Therefore, the aim of this study was to compare the bonding characteristics and interactions of hydraulic calcium silicate based dentine replacement materials to CAD and sound dentine. The null hypothesis was that the bond of these material to CAD does not differ from sound dentine and pretreatment of dentine with NaOCl does affect their bond strength.

2. Materials and methods

Three hydraulic calcium silicate-based materials were assessed. These included:

- Retro MTA (BioMTA, Seoul, Korea)
- Biodentine (Septodont, Saint Maur des Fosses, France)
- Theracal LC (Bisco, Schaumburg, IL, USA).

The materials were prepared according to manufacturer's instructions. Once set, they were placed in Hank's balanced salt solution (HBSS, H6648, Sigma Aldrich, St. Louis, MO, USA) for 1 week and 24 weeks time periods. At each time point the set material were removed from solution and were dried in a vacuum desiccator and tested.

2.1. Material characterization

Cylindrical specimens 10 mm in diameter and 2 mm high were prepared. At each time point the specimens were removed from solution, dried and prepared for characterization. Three replicates were prepared for each test. The three materials were characterized by using scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis. For scanning electron microscopy the dried specimens were impregnated in resin (Epoxyfix, Struers GmbH, Ballerup, Denmark) under vacuum. The resin blocks were then ground with progressively finer diamond discs and pastes using an automatic polishing machine (Tegramin 20, Struers GmbH, Ballerup, Denmark). The specimens were mounted on aluminum stubs, carbon coated and viewed under the scanning electron microscope (Zeiss MERLIN Field Emission SEM, Carl Zeiss NTS GmbH, Oberkochen, Germany). Scanning electron micrographs of the different material microstructural components at different magnifications in back-scatter electron mode for the polished samples were captured and energy dispersive spectroscopy (EDS) was also performed.

For phase analysis the dried materials were crushed to a fine powder using an agate mortar and pestle. Phase analysis of the powders was performed using a Bruker D8 diffractometer (Bruker Corp., Billerica, MA, USA) with Co K α radiation (1.78 Å). The X-ray patterns were acquired in the 2 θ (15–45°) with a step of 0.02° and 0.6 s per step. Phase identification was accomplished using a search-match software utilizing ICDD database (International Centre for Diffraction Data, Newtown Square, PA, USA).

2.2. Assessment of bond strength of the materials to caries affected dentine

Human posterior teeth were used for this experiment. They were extracted for various reasons and were kept in water until use. Two types of dentine blocks (60 each) were prepared. One set was from sound dentine and the other from caries affected dentine. For sound dentine caries free teeth were selected, the enamel was trimmed from the surface of teeth with a gypsum model trimmer to achieve a flat dentine surface. For carious dentine specimens, molar teeth with class 1 occlusal carious lesions were selected. To expose the caries-affected dentine the enamel portion was trimmed in a gypsum model trimmer to allow direct access to the carious dentine. The carious lesions in dentine were then removed with a manual excavator assisted by a caries detector dye (Seek, Ultradent, USA). Reaching the hard dentine layer was verified by dentine resistance to excavation, color and visual inspection. Both

caries-free and caries-affected dentine specimens were standardized by assessment of the surface hardness evaluated by Vickers microhardness testing (Bareiss Prufgeratebau GmbH, Oberdischingen, Germany). Caries affected dentinal blocks with an average microhardness of 50–55 HV were selected. Sound dentine specimens were standardized by microhardness values (100–105 HV) [18].

All specimens (sound and affected dentine) were mounted in acrylic resin. Half of the affected and sound dentine blocks were pretreated with 5 mL of 5.25% NaOCl prior to material placement. After pretreatment with NaOCl and before material placement specimens were finally rinsed with normal saline. The microstructure of the affected and sound dentine was evaluated by scanning electron microscopy before and after pretreatment with NaOCl to evaluate the effect of the pretreatment on the dentine microstructure. The dentine specimens that were pretreated with NaOCl are referred to as hypomineralized dentine. Stereomicroscopic images (Olympus SZ30, Olympus, Japan) of the dentine before and after pretreatment were also captured.

A polyvinyl mold (3.5 mm diameter and 3 mm height) was placed over the middle of the flattened dentinal surface of blocks. Biodentine and Retro MTA were prepared according to the manufacturer's instructions. Theracal LC was light cured for 20 s at 600 mW/cm² using an LED light source. Moulds were removed after (15 min) confirming the initial set of the cement. All specimens were then be incubated at 37 °C in fully saturated conditions. Half of the specimens of each subgroup were incubated for 1 week and the other half were incubated for 24 weeks.

Shear bond strength assessment was performed after incubation by a universal testing machine (Z050, Zwick/Roell, Ulm, Germany) with a chisel-edge plunger edge aimed at the dentine replacement material/adhesive interface with a speed of 0.5 mm/min. Shear bond strength in Nmm-2 was calculated by dividing the peak load at failure by the specimen surface area. Failure modes were evaluated by a single operator under a stereomicroscope (Olympus SZ30, Olympus, Japan) at ×20 magnification. Failure modes were categorized in one of the following groups:

Mode 1. Adhesive failure that occurred at the filling material and dentine interface

Mode 2. Cohesive failure within the filling material

Mode 3. Mixed failure mode

2.3. Assessment of radiopacity

The dentinal blocks were placed on a digital sensor (RVG 5000 Kodak; Eastman Kodak Company, Vincennes, France) and fixed with wax in a way that the dentine surface in which would come in contact with dentine replacement materials and was going to be evaluated was perpendicular to the sensor's surface. All specimens were placed at a 30 cm distance for 0.32 s in a dental X-ray unit (70 kVp/7 mA) connected to a digital system (Kodak RVG 5000 Trophy for Eastman Kodak Company). The X-ray unit was kept in the same position throughout the experiment. The radiographic images were saved in JPEG format and stored directly on a computer connected to the digital system through its software (KDIS 6.8 Patient File; Eastman Kodak Company Digital analysis proce-

dures). The same procedure was done on the specimens after shear bond testing. The radio-opacity (in pixels) of the surface of each sample was determined in the digital radiographs by densitometry analysis of the Kodak software. The average opacity of the surface was provided by the software.

2.4. Statistical analyses

The data were evaluated using Statistical Package for the Social Sciences software (PASW Statistics 18; SPSS Inc., Chicago, IL). One-way analysis of variance and Tukey post-hoc tests at a significance level of $P=0.05$ were used to perform multiple comparison tests.

3. Results

3.1. Material characterization

The scanning electron micrographs and energy dispersive spectroscopic plots of the three test materials are shown in Fig. 1a and b. The XRD scans are shown in Fig. 2. From the scanning electron micrographs it was evident that Biodentine matured faster than the Retro MTA but by 24 weeks the Retro MTA also exhibited reaction rims around the cement particles from the hydration process. After 1 week immersion in HBSS the cement particles of Theracal did not show any signs of hydration. Reaction rims were observed after 24 weeks of immersion but the reaction rims were still very discreet. The EDS analyses for all materials showed strong peaks for calcium, silicon and oxygen as part of the tricalcium silicate cement. Both Retro MTA and Biodentine showed peaks for zirconium. Both Retro MTA and Theracal exhibited a peak for aluminium indicating the presence of an aluminium rich phase in the cement. The Theracal showed a strontium peak on EDS analyses but this was not evident in the XRD scan thus indicating the glassy amorphous phase. No changes in the EDS analyses was observed at the different time periods tested.

The XRD scans also show the similar maturation for both Biodentine and Retro MTA at 24 weeks with the formation of calcium hydroxide and obliteration of the tricalcium silicate peaks at 32° showing their hydration. The slower reaction of the Theracal was evident even in the XRD scans as at both 1 week and 24 weeks no calcium hydroxide peaks were visible. Some reaction of the tricalcium silicate was evident as there was a reduction in peak height of this phase at 32 and 34° after 24 weeks of immersion in solution (Fig. 2).

3.2. Shear bond strength

The results of shear bond strength of the pulp capping materials to different types of dentine substrate after 1 and 24 weeks is shown in Fig. 3a. There was no difference in the bond strengths of the different materials to the dentine ($P>0.05$) after 1 week. The bond strengths of Retro MTA to intact dentine was higher than to intact dentine pretreated with NaOCl and affected dentine ($P=0.049$, $P=0.021$ respectively). Theracal also exhibited deterioration in bond strength when bonding to intact dentine pretreated with NaOCl and affected dentine ($P<0.001$, $P=0.003$ respectively) but not to affected dentine

pretreated with NaOCl ($P=0.075$). Biodentine demonstrated similar bond strengths on all dentine types ($P>0.05$).

After 24 weeks there was a difference in the bond strengths on intact dentine for all materials tested with Retro MTA and Biodentine showing higher bond strengths after maturation ($P<0.001$). No change was observed for Theracal where values remained stable with no improvement in bond strengths with maturation ($P>0.05$). No changes were observed on pretreated hypomineralized dentine for all materials where shear bond strength values were every low at both time frames.

The Retro MTA and Biodentine exhibited a higher bond strength after 24 weeks on affected dentine ($P<0.001$) but no change was observed in Theracal over the 24 week period ($P=1$). When the affected dentine was pre-treated, the bond

strengths improved and this was enhanced with increasing material maturity ($P<0.001$).

The bond strengths were effected by material maturation in Biodentine and Retro MTA and also by the pretreatment with sodium hypochlorite. In sound dentine the pre-treatment deteriorated the bond strength but an improvement was observed in affected dentine. The failure mode was mostly mixed for all material tested on all dentine substrates. The different types of failure modes are shown in Fig. 3b. A large number of Theracal specimens detached prior to testing after being subjected to 6 months immersion in fluids.

The electron micrographs of the dentine blocks are seen in Fig. 4a showing the different microstructure of the dentine. Surface deposits were evident in intact dentine and the

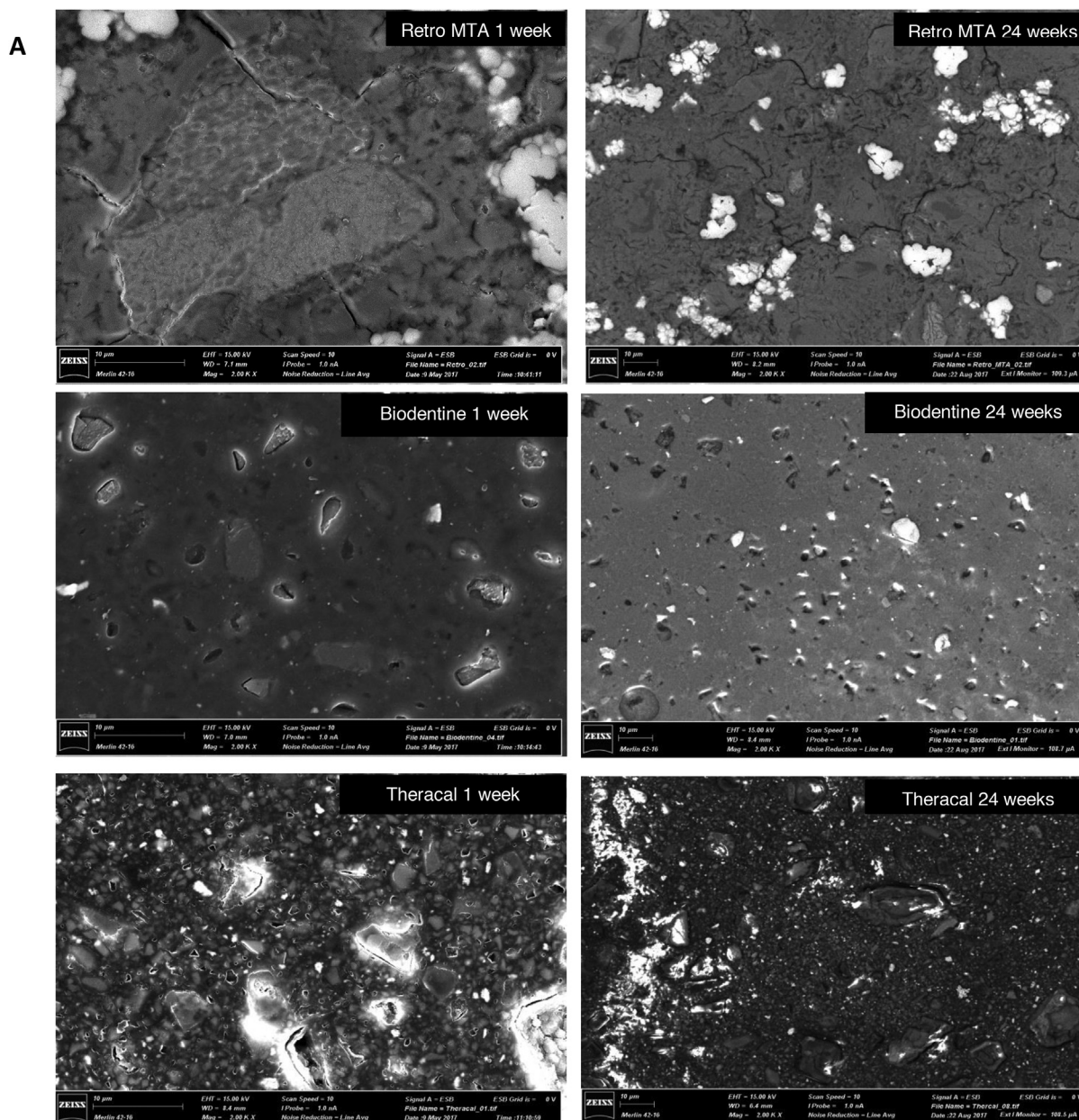


Fig. 1 – (a) Back scatter scanning electron micrographs of the test materials after 1 week and 24 weeks immersion in Hank's balanced salt solution. (b) Energy dispersive spectroscopy plots of the test materials after 1 week and 24 weeks immersion in Hank's balanced salt solution.

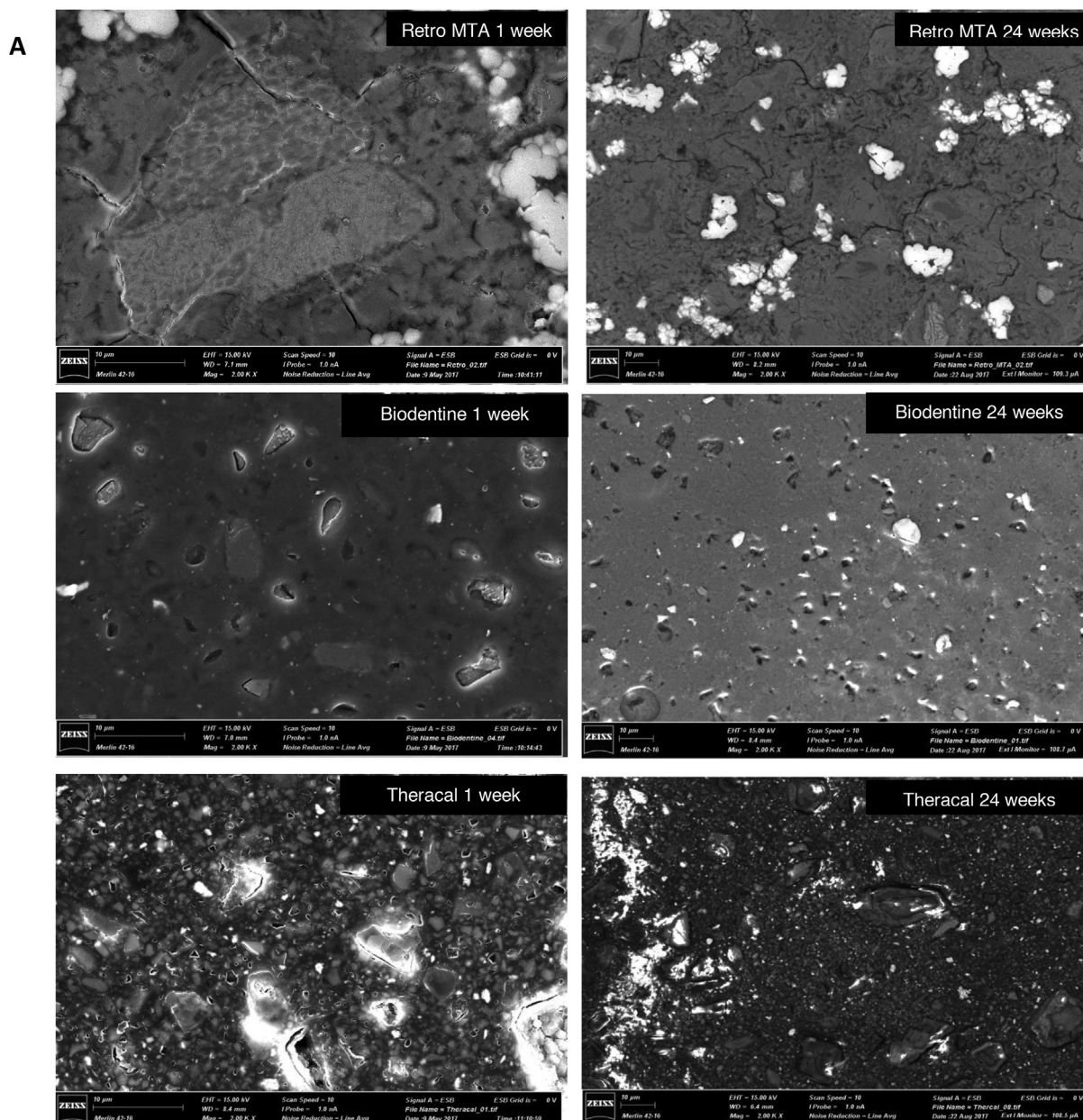


Fig. 1 – (Continued)

deposits increased after pre-treatment with sodium hypochlorite. Less surface deposits were present in affected dentine but sodium hypochlorite application increased the intensity of these deposits even in affected dentine. The stereo micrographs exhibited a change in colour for the affected dentine when pre-treated with sodium hypochlorite as indicated in Fig. 4b.

3.3. Changes in radiopacity of dentine blocks

The changes in radiopacity after 1 week and after 24 weeks of application of the materials on the different dentine substrates is shown in Fig. 5. All the materials exhibited a similar radiopacity after 1 week of application. There was no change in radiopacity of the dentine after 1 week assessment. After

24 weeks the Retro MTA and Theracal exhibited a change in radiopacity of intact dentine ($P < 0.001$). The hypomineralized intact dentine and both types of affected dentine was modified by all the materials exhibiting a rise in radiopacity after 24 weeks exposure ($P < 0.001$).

4. Discussion

In the current study the bonding characteristics and interactions of a number of dentine replacement materials was investigated. The materials were chosen on purpose as they are all based on hydraulic calcium silicate but they had different chemistries. The Retro MTA is basic mineral trioxide aggregate formulation with no additives to enhance its char-

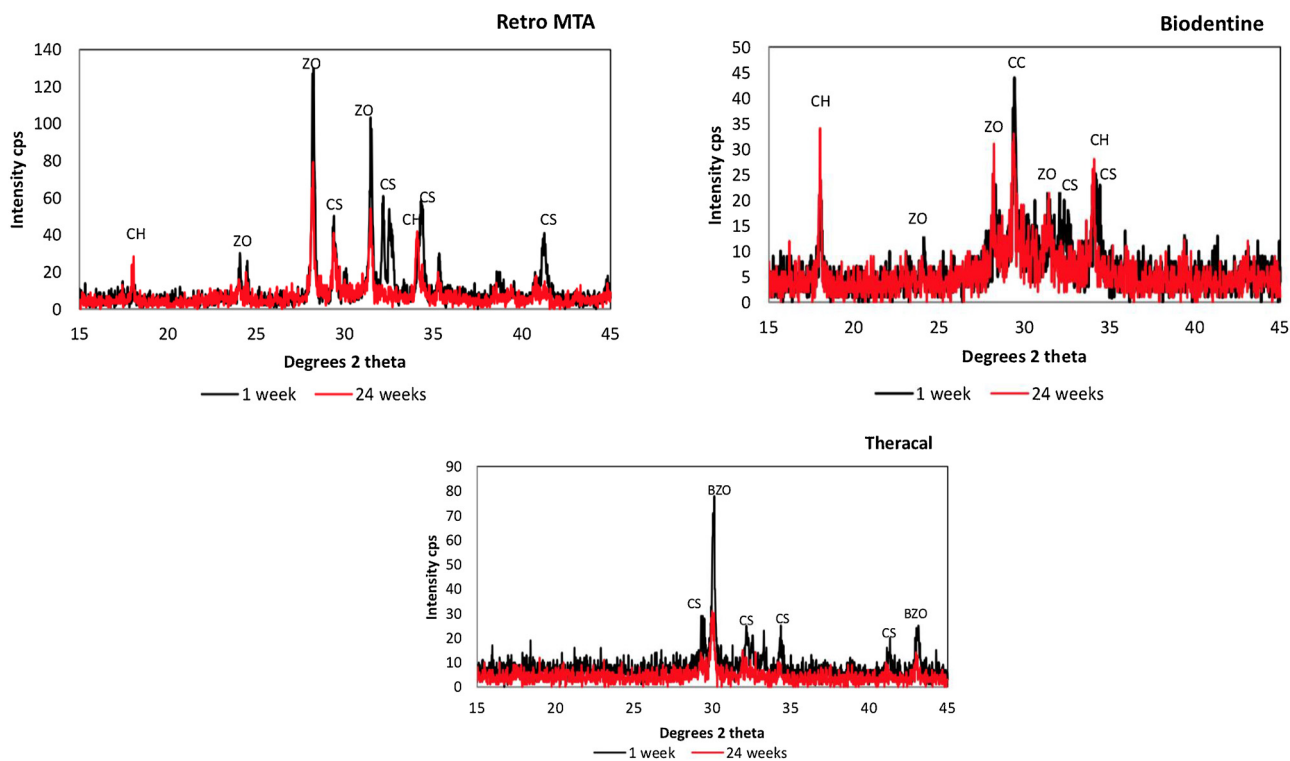


Fig. 2 – X-ray diffraction scans of the test materials after immersion in HBSS for 1 and 24 weeks (BZO: barium zirconate; CC calcium carbonate; CH: calcium hydroxide; CS tricalcium silicate; ZO: zirconium oxide).

acteristics. Biodentine is a new generation material which includes additives and thus enhanced calcium ion release [14,15,19]. Theracal is resin based and thus releases less calcium [14,15]. The materials were characterized to show the specific material features. Although all the materials had a tricalcium silicate phase they showed different hydration characteristics which could account for their diverse behavior in contact with dentine. The Biodentine and Retro MTA were both water-based but due to its additives, Biodentine reacted faster and produced calcium hydroxide earlier than Retro MTA. This was evident from the reaction rims shown in the electron micrographs and the calcium hydroxide peaks shown in the XRD scans. The long term formation of calcium hydroxide had more effect on the remineralization and also the long term bond strength thus Retro MTA exhibited better bond strengths and more remineralization than Biodentine. Theracal, which is resin based and exhibited very slow hydration and no formation of crystalline calcium hydroxide showed poor bonding.

The null hypothesis of this investigation was rejected as difference was seen in the shear bond strength of the evaluated dentine replacement materials to sound and CAD. Also, in sound dentine the pre-treatment with NaOCl, deteriorated the bond strength but an improvement was observed in CAD. In clinical cases of pulp capping these dentine replacement materials come in contact with CAD. CAD is partially demineralized and therefore more porous and softer than sound dentine, has narrow and obliterated dentinal tubules due to deposition of intratubular dentine and has a hybrid layer thicker than that of sound dentine [2–4]. Due to these differ-

ences, the bonding characteristics and interactions between dentine replacement materials and CAD may differ from sound dentine. Therefore, this evaluation is of clinical relevance. Many studies have shown that the bond strength values of restorative materials to sound dentine is higher than that of CAD [5,6]. In the current study, the pretreatment of affected dentine with NaOCl, improved the material bond strength as in previous literature [8]. It is important to have good marginal seal and better bond strength for the longevity of and success of pulp capping. Better bonding to dentine reduces marginal leakage and subsequently reduced the incidence of secondary caries, post-operative sensitivity and pulpal pathology [20].

The bond strength of Biodentine and Retro MTA increased over time. This is due to progression in hydration and maturation [21] of these cements as seen in XRD analysis. At 24 weeks peaks for calcium hydroxide were present and the tricalcium silicate peaks disappeared. With progression in maturation and hydration calcium hydroxide crystalline structures are formed due to saturation of the soluble form [22]. The apposition of crystalline structures may improve the mechanical bond between these cements and dentine. No change was observed in bond strength values of Theracal over time. This may be due to its compromised hydration and maturation. According to XRD evaluations no calcium hydroxide peaks were visible on the XRD plots at 24 weeks but some reaction of the tricalcium silicate was evident. Contrary to Biodentine and Retro MTA, Theracal does not include water in its formulation and therefore, this material's hydration completely depends on the water taken up from the environment and its diffusion within the material [15]. Thus, the hydration of this mate-

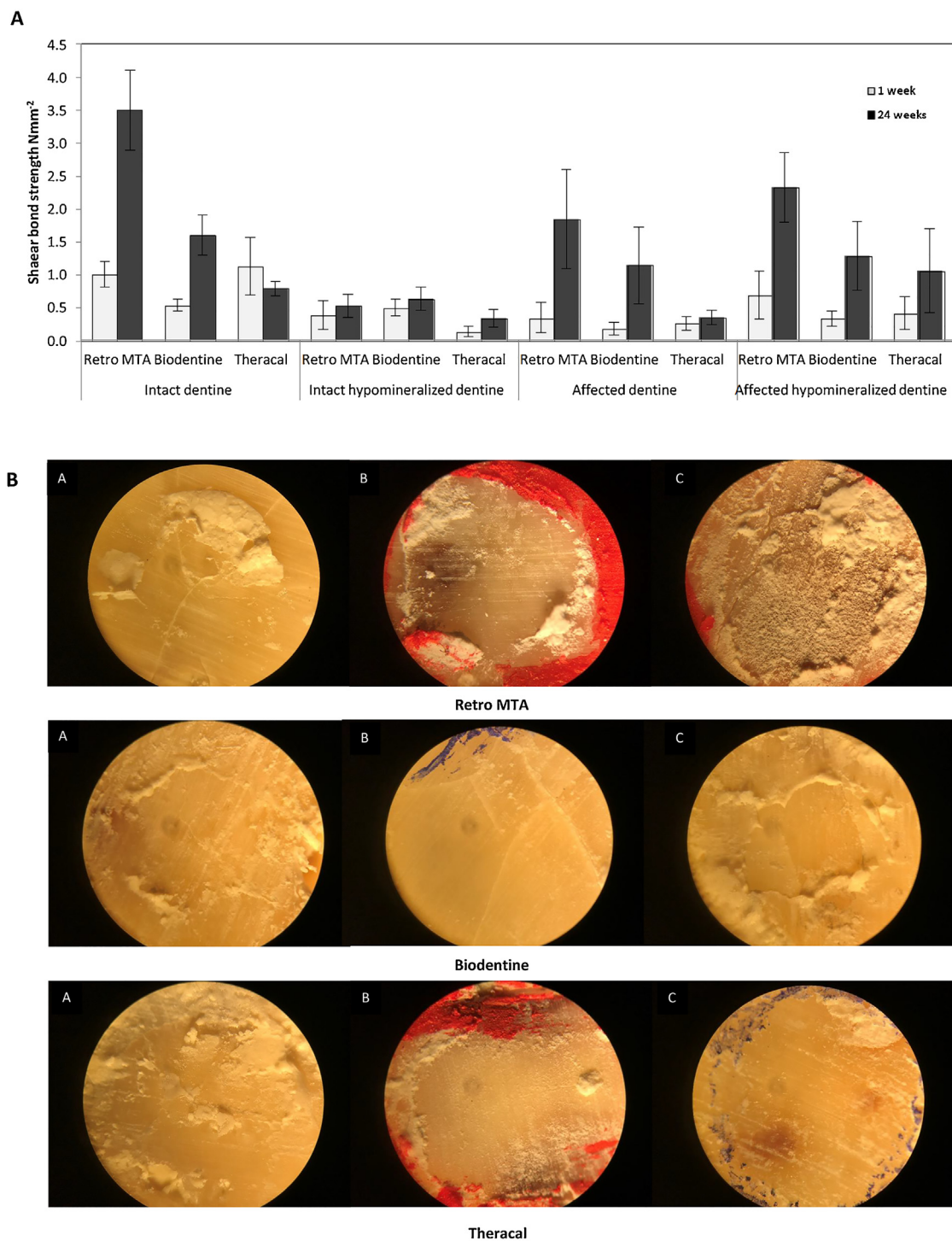


Fig. 3 – (a) Results of shear bond strength of test materials to different dentine substrates \pm SD. (b) Images of failed specimens after shear bond strength testing. A: Intact dentine; B: Affected dentine and C: Affected dentine after pretreatment with NaOCl showing mixed failure modes.

rial may be compromised when compared with water-based materials such as Biodentine as seen in this study.

The bonding mechanism of Biodentine to intact dentine has already been postulated. It was shown that transfer of calcium ions occurs across the tooth to material interface creating a mineral infiltration zone [16]. This hypothesis was

discredited by a further study where no mineral transfer was shown at the interface [17].

In sound dentine the pre-treatment deteriorated the bond strength but an improvement was observed in affected dentine. The microstructure of caries affected dentine and sound dentine is different as shown in the scanning electron micro-

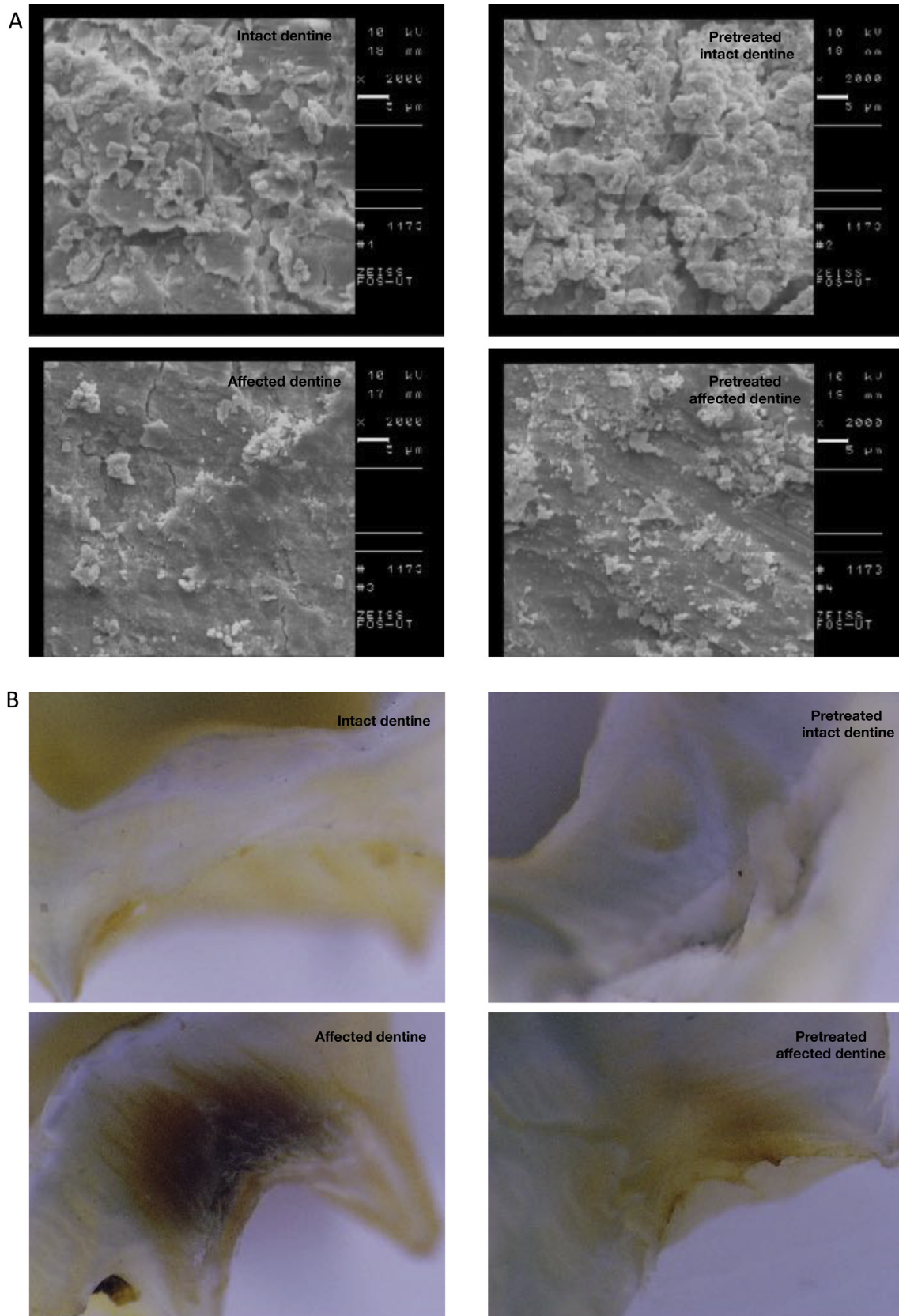


Fig. 4 – (a) Scanning electron micrographs of the different types of dentine used in the experiment (mag. 2K \times). (b) Stereo-microscopic images of the different types of dentine used during the experimental procedures.

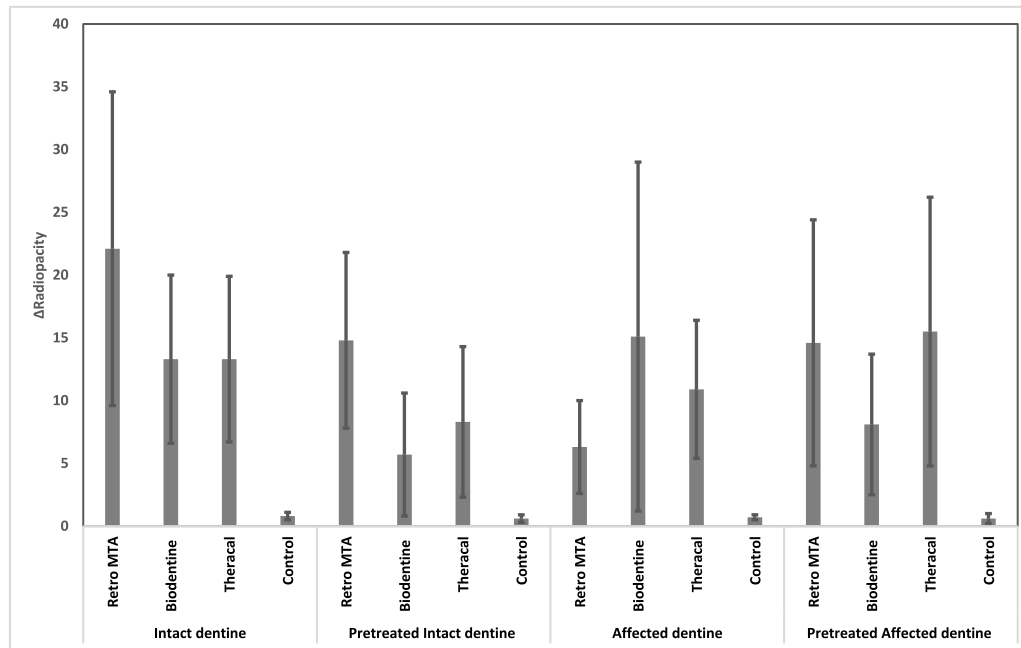


Fig. 5 – Changes in radiopacity of the dentine blocks over time when using the test materials.

graphs. The pretreatment with sodium hypochlorite further changed the dentine microstructure. This pattern was also seen in the case of bonding to restorative materials [8]. Improvement of bond strength to CAD after pretreatment with NaOCl was expected as it causes dissolution of superficial organic components of smear layer in this type of dentine therefore allowing better contact between the cements and CAD.

Over time the radiopacity of intact dentine increased in specimens in contact with Retro MTA and Theracal. This may be due to either remineralization of dentine over the 24 week period or migration of elements [23] such as zirconium or aluminum from dentine replacement materials to dentine. In the case of Retro MTA as progression in hydration and maturation was seen, remineralization of dentine can be considered. But in the case of Theracal as its hydration was compromised migration of elements may be a more probable cause for the increase in opacity. This is in agreement with recent studies where remineralization was observed in dentine following the placement of hydraulic calcium silicate-based dentine replacement materials [24,25]. In one of the studies intact dentine was used and calcium ion transfer was shown to happen together with the formation of calcium phosphate at the interface [25]. In the other study [24] the dentine was demineralized with formic acid. Although this is valid in vitro, formic acid can affect the hydration of hydraulic calcium silicate-based materials [26] thus is not suitable to use on dentine as traces of it may affect the hydration thus the remineralization process. Further research is required to evaluate the mechanisms of remineralization and bonding mechanisms of dentine replacement materials to caries affected dentine. The clinical relevance of this is very clear. Studies of material bond strengths to sound dentine are of limited value clinically as verified in this study.

5. Conclusion

Biodentine and Retro MTA showed better bonding to CAD. Pretreatment of CAD with NaOCl improved the bond strength of silicate-based dentine replacement materials to CAD.

Acknowledgements

Ing James Camilleri of the Department of Metallurgy and Materials Engineering for his technical expertise. ERDF (Malta) for the financing of the testing equipment through the project: “Developing an Interdisciplinary Material Testing and Rapid Prototyping R&D Facility” (Ref. no. 012).

REFERENCES

- [1] Fusayama T. Two layers of carious dentin; diagnosis and treatment. *Oper Dent* 1979;4:63–70.
- [2] Kuboki Y, Ohgushi K, Fusayama T. Collagen biochemistry of the two layers of carious dentin. *J Dent Res* 1977;56:1233–7.
- [3] Nakornchai S, Atsawasuwana P, Kitamura E, Surarit R, Yamauchi M. Partial biochemical characterisation of collagen in carious dentin of human primary teeth. *Arch Oral Biol* 2004;49:267–73.
- [4] Fusayama T. Intratubular crystal deposition and remineralization of carious dentin. *J Biol Buccale* 1991;19:255–62.
- [5] Nicoloso GF, Antoniazzi BF, Lenzi TL, Soares FZM, Rocha RO. The bonding performance of a universal adhesive to artificially-created caries-affected dentin. *J Adhes Dent* 2017;19:317–21.
- [6] Kucukyilmaz E, Savas S, Kavrik F, Yasa B, Botsali MS. Fluoride release/recharging ability and bond strength of glass

- ionomer cements to sound and caries-affected dentin. *Niger J Clin Pract* 2017;20:226–34.
- [7] Erhardt MC, Toledano M, Osorio R, Pimenta LA. Histomorphologic characterization and bond strength evaluation of caries-affected dentin/resin interfaces: effects of long-term water exposure. *Dent Mater* 2008;24:786–98.
- [8] Taniguchi G, Nakajima M, Hosaka K, Iwamoto N, Ikeda M, Foxton RM, et al. Improving the effect of NaOCl pretreatment on bonding to caries-affected dentin using self-etch adhesives. *J Dent* 2009;37:769–75.
- [9] Haj-Ali R, Walker M, Williams K, Wang Y, Spencer P. Histomorphologic characterization of noncarious and caries-affected dentin/adhesive interfaces. *J Prosthodont* 2006;15:82–8.
- [10] Grech L, Mallia B, Camilleri J. Investigation of the physical properties of tricalcium silicate cement-based root-end filling materials. *Dent Mater* 2013;29(February (2)):e20–8.
- [11] Pornamazeh T, Yadegari Z, Ghasemi A, Sheykh-Al-Eslamian SM, Shojaeian S. In vitro cytotoxicity and setting time assessment of calcium-enriched mixture cement, retro mineral trioxide aggregate and mineral trioxide aggregate. *Iran Endod J* 2017;12:488–92.
- [12] Suh B, Yin R, Cannon M, Martin DE. Polymerizable dental pulp healing, capping, and lining material and method for use. Google Patents; 2008.
- [13] Gandolfi MG, Siboni F, Prati C. Chemical-physical properties of TheraCal, a novel light-curable MTA-like. *Int Endod J* 2012;45:571–9.
- [14] Camilleri J. Hydration characteristics of Biodentine and Theracal used as pulp capping materials. *Dent Mater* 2014;30:709–15.
- [15] Camilleri J, Laurent P, About I. Hydration of Biodentine, Theracal LC, and a prototype tricalcium silicate-based dentin replacement material after pulp capping in entire tooth cultures. *J Endod* 2014;40(November (11)):1846–54.
- [16] Atmeh AR, Chong EZ, Richard G, Festy F, Watson TF. Dentin-cement interfacial interaction: calcium silicates and polyalkenoates. *J Dent Res* 2012;91:454–9.
- [17] Li X, Pongprueksa P, Van Landuyt K, Chen Z, Pedano M, Van Meerbeek B, et al. Correlative micro-Raman/EPMA analysis of the hydraulic calcium silicate cement interface with dentin. *Clin Oral Invest* 2016;20:1663–73.
- [18] Shibata S, Vieira LC, Baratieri LN, Fu J, Hoshika S, Matsuda Y, et al. Evaluation of microtensile bond strength of self-etching adhesives on normal and caries-affected dentin. *Dent Mater J* 2016;35:166–73.
- [19] Camilleri J, Sorrentino F, Damidot D. Investigation of the hydration and bioactivity of radiopacified tricalcium silicate cement, Biodentine and MTA Angelus. *Dent Mater* 2013;29:580–93.
- [20] Dammaschke T, Stratmann U, Fischer RJ, Sagheri D, Schafer E. A histologic investigation of direct pulp capping in rodents with dentin adhesives and calcium hydroxide. *Quintessence Int* 2010;41:e62–71.
- [21] Grazziotin-Soares R, Nekoofar MH, Davies T, Hubler R, Meraji N, Dummer PMH. Crystalline phases involved in the hydration of calcium silicate-based cements: semi-quantitative Rietveld X-ray diffraction analysis. *Aust Endod J* 2017, <http://dx.doi.org/10.1111/aej.12226> [Epub ahead of print].
- [22] Niu LN, Jiao K, Wang TD, Zhang W, Camilleri J, Bergeron BE, et al. A review of the bioactivity of hydraulic calcium silicate cements. *J Dent* 2014;42:517–33.
- [23] Meraji N, Camilleri J. Bonding over dentin replacement materials. *J Endod* 2017;43:1343–9.
- [24] 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;33:434–45.
- [25] Atmeh AR, Chong EZ, Richard G, Boyde A, Festy F, Watson TF. Calcium silicate cement-induced remineralisation of totally demineralised dentine in comparison with glass ionomer cement: tetracycline labelling and two-photon fluorescence microscopy. *J Microsc* 2015;257:151–60.
- [26] Cerny R, Rovnaníková P. Transport processes in concrete. CRC Press; 2002.