

EFFECT OF BTS CONTENT ON MICROSTRUCTURE AND DIELECTRIC PROPERTIES OF 0-3 BTS CERAMIC/ACSA CEMENT COMPOSITES

Widchaya Somsri¹, Thanya Udeye^{1,2}, Naratip Vittayakorn³, Phongthorn Julphunthong^{2,4}, Aurawan Rittidech⁵ and Theerachai Bongkarn^{1,2,*}

Received: October 31, 2024; Revised: January 28, 2025; Accepted: February 01, 2025

Abstract

The effect of $\text{BaTi}_{0.91}\text{Sn}_{0.09}\text{O}_3$ (BTS) ceramic content (between 30 to 70 % volume) on microstructure and dielectric properties of BTS/Alite calcium sulfoaluminate cement composites was studied. The BTS ceramic was fabricated by the conventional solid-state reaction method. The powders and ceramics were calcined and sintered at the temperatures of 1,200°C for 2 h and 1,400°C for 4 h, respectively. The 0-3 dielectric composite consisted of BTS as the dielectric phase and ACSA as the matrix phase and were produced by the pressing and curing technique. The SEM micrographs illustrated a typical interfacial transition zone (ITZ) between the BTS ceramics and the ACSA cement matrix and there was a slight increase of pores when BTS content increased. Effective binding was observed at 30, 40, and 50 volume % BTS while increased cracking of BTS ceramics was observed at the ITZ boundary as the BTS ceramic content increased to 60 and 70 %. The dielectric constant (ϵ_r) at 1 kHz increased with increased BTS ceramic content, up to 50 volume %, and then decreased due to the presence of pores and cracks in the BTS ceramic phase. The dielectric loss ($\tan \delta_r$) at 1 kHz decreased as the ceramic content increased, while the dielectric constant (ϵ_r) followed the predictions of the cubic model. It appeared that the ceramics were randomly distributed in the composite. The values of ϵ_r and $\tan \delta_r$ decreased with increased frequencies, measured in the range of 1-1,000 kHz.

Keywords: ACSA cement; BTS ceramic; Composites; Dielectric properties

¹ Department of Physics, Faculty of Science, Naresuan University, Phitsanulok, 65000, Thailand. E-mail: wichayas67@nu.ac.th, thanyau@nu.ac.th, researchcmu@yahoo.com*

² Research Center for Academic Excellence in Applied Physics, Faculty of Science, Naresuan University, Phitsanulok, 65000, Thailand. E-mail: thanyau@nu.ac.th, phongthornj@nu.ac.th, researchcmu@yahoo.com*

³ Advanced Materials Research Unit, Faculty of Science, King Mongkut's Institute of Technology Ladkrabang, Bangkok, 10110, Thailand. E-mail: naratip.vi@kmitl.ac.th

⁴ Department of Civil Engineering, Faculty of Engineering, Naresuan University, Phitsanulok 65000, Thailand. E-mail: phongthornj@nu.ac.th

⁵ Department of Physics, Faculty of Science, Mahasarakham University, Mahasarakham 44150, Thailand. E-mail: au_wow@yahoo.com

* Corresponding author

Introduction

Cement-based piezoelectric composites were created in 2002. They have found widespread use in diverse civil engineering applications, serving as sensors and actuators for monitoring material defects in concrete structures like bridges, tunnel linings, hillside structures, and smart buildings in real-time (Li *et al.*, 2001; Dong and Li, 2005; Li *et al.*, 2006; Xin *et al.*, 2010).

In the past, composite materials, particularly dielectric/cement composites, have been studied for their applications in smart infrastructure and structural health monitoring (SHM). These composites combine the mechanical strength and durability of traditional cement with enhanced electrical properties, making them suitable for a variety of advanced uses. Lead-based materials have been utilized as the primary ingredient to create composite materials such as Portland cement mixed with lead magnesium niobate/lead titanate (PMN-PT), lead zirconate titanate (PZT), or lead niobium-magnesium zirconate titanate (P(MN)ZT) (Li *et al.*, 2002; Jaitanong *et al.*, 2011; Santos *et al.*, 2020). Due to the inclusion of lead-based ceramics, the materials exhibit excellent electrical properties and can be applied to a variety of uses. However, PbO can volatilize during the sintering process, thereby causing environmental concerns. Consequently, there is a compelling motivation to explore the development of lead-free ceramics as a viable alternative to their lead-based equivalents.

Barium tin titanate ceramics, a lead-free ceramic type, are well known for their remarkable electrical and piezoelectric properties. Liu *et al.* (2017) fabricated $\text{BaTiO}_3\text{-Sn}_x$ ceramics with $x = 2, 6, 8, 9, 10$, and 11 mol% via the conventional solid-state reaction method. The $\text{BaTiO}_3\text{-Sn}_x$ ceramics exhibited coexisting orthorhombic and tetragonal phases, and the highest piezoelectric coefficient ($d_{33} = 920$ pC/N) was observed at a temperature of 50°C with $x = 9$ mol%. Yao *et al.* (2012) synthesized $\text{BaTiO}_3\text{-Sn}_x$ ceramics via the conventional solid-state reaction method. The $\text{BaTiO}_3\text{-Sn}_x$ ceramics were calcined at $1,200^\circ\text{C}$ for 2 h and sintered at $1,400^\circ\text{C}$ for 4 h. The $\text{BaTiO}_3\text{-Sn}_x$ ceramics exhibited a quasi-quadruple point, a condition where four phases (cubic, tetragonal, orthorhombic, and rhombohedral) nearly coexist together in the temperature-composition phase diagram. At this composition of $\text{BaTiO}_3\text{-Sn}_x$ with $x = 11$ mol %, the dielectric permittivity reaches approximately 75,000, which is 6-7 times higher compared to pure BaTiO_3 . Additionally, d_{33} reached 697 pC/N, showing a 5-fold increase compared to pure BaTiO_3 .

Many researchers have successfully prepared 0-3 lead-free Portland cement composites, as demonstrated by Rianyoi *et al.* (2011). They fabricated barium titanate (BT) and Portland cement composites with 0-3 connectivity, achieving BT concentrations of 30%, 50%, and 70% by volume through the mixing and pressing method. They found that the dielectric constant (ϵ_r) of BT/Portland cement composites increased as BT concentration increased, and that the highest value for ϵ_r , of 436, was obtained at a BT concentration of 70%. In addition, the dielectric loss ($\tan \delta_r$) decreased with increased BT concentration.

Calcium sulfoaluminate (CSA) cement is an innovative supplementary cementitious material utilized as an alternative binder to ordinary Portland cement (OPC) or as a partial substitute for OPC (Juenger *et al.*, 2011). Significant energy savings can be achieved with CSA cement due to its lower firing temperature, approximately 200°C lower than that of OPC (Bullerjahn *et al.*, 2014; Hargis *et al.*, 2014; Rungchet *et al.*, 2017). Additionally, CSA cement is easier to grind compared to OPC. Compared to the practical engineering properties of OPC concrete, CSA cement offers higher early strength, faster setting time, reduced shrinkage, and enhanced sulfate resistance (El-Alfi and Gado, 2016). CSA cement is commonly used in niche applications, partly because considerable amounts of expensive alumina are required during fabrication. Alite calcium sulfoaluminate (ACSA) cement is a type of CSA cement. The engineering properties of CSA cement are enhanced in ACSA cement owing to the presence of alite (C_3S , the main phase of OPC), $\text{C}_4\text{A}_3\text{S}$, and C_2S as the main phase composition. Tiantong *et al.* (2022) successfully fabricated a 0-3 KNLNTS piezoelectric ceramic/alite calcium sulfoaluminate cement composite. Their study demonstrated that ACSA clinkers were effectively synthesized at a firing temperature of $1,250^\circ\text{C}$. To mitigate sulfur loss, it is necessary to double the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ content in the raw mixture. The dielectric properties and piezoelectric coefficients were found to be strongly correlated with the KNLNTS ratio as an increase in the KNLNTS content significantly enhanced both the dielectric and piezoelectric properties.

The properties of 0-3 connectivity lead-free dielectric ceramic-cement composites are influenced by various factors, including the fabrication method and ceramic content (Rianyoi *et al.*, 2011; Potong *et al.*, 2009). Therefore, this study focused on investigating the impact of $\text{BaTi}_{0.91}\text{Sn}_{0.09}\text{O}_3$; BTS ceramic content on the

microstructure and dielectric properties of 0-3 connectivity lead-free BTS/ACSA cement composites in the ceramics:cement ratios of 30:70, 40:60, 50:50, 60:40, and 70:30.

Materials and Method

The $\text{BaTi}_{0.91}\text{Sn}_{0.09}\text{O}_3$ ceramic was synthesized using the solid state reaction technique. The starting materials were high purity oxide and carbonate powders of BaCO_3 (99.0%, HiMedia, IN), TiO_2 (99%, KemAus, AU) and SnO_2 (99.9%, Aldrich, MX). The materials were mixed to the correct stoichiometric ratio in ethanol by milling with zirconia balls for 24 h. Thereafter, the suspensions were dried at a temperature of 100°C . The mixed powders were calcined at a temperature of $1,200^\circ\text{C}$ for 2 h (Yao *et al.*, 2012) with a heating rate of $5^\circ\text{C}/\text{min}$. The calcined powders were ball milled with 3 wt% polyvinyl butyral (PVB) in ethanol for 12 h, then dried at 100°C . The powders were pressed into pellets at a pressure of 80 MPa with a diameter of ≈ 15 mm and a thickness of ≈ 1.5 mm. The pellets were sintered at $1,400^\circ\text{C}$ for 4 h with a heating rate of $5^\circ\text{C}/\text{min}$ after burning out the binder at 400°C for 3 h.

The BTS ceramic pellets were then grounded and sieved to a particle size of 300-600 μm (Potong, *et al.*, 2009). The ground powders were mixed with alite calcium sulfoluminate cement (Tiantong *et al.*, 2022) to prepare five different experimental BTS/ACSA cement composites (0-3 connectivity) with BTS volumes of 30, 40, 50, 60, and 70%. The samples were pressed and cured in a chamber with a relative humidity of 98% at a temperature of 60°C for 1 day. This process facilitated the hydration of the cement, effectively binding the composite. Subsequently, the pellets were subjected to oven drying at 60°C for 3 days (Chomyen *et al.*, 2018)

to remove free water in the cement paste. The temperature was limited to 60°C to prevent ettringite dehydration (Alarcon-Ruiz *et al.*, 2005 ; Chaipanich and Nochaiya, 2010; Nochaiya *et al.*, 2010; Wongkeo *et al.*, 2013).

A scanning electron microscope (SEM) with energy-dispersive X-ray spectrometry (EDS) was employed to examine morphological features and analyze the elemental composition of the composites. In order to prepare the composite for the measurement of their electrical properties, each pellet was coated with silver paint on both the surfaces. The dielectric behavior of the samples was measured using an LCR meter (HP, 4284A) at frequencies between 1-1,000 kHz. The relative dielectric constant (ϵ_r) was calculated as follows:

$$\epsilon_r = \frac{Cd}{\epsilon_0 A}$$

where C is the capacitance of the sample, d is the thickness, ϵ_0 is the permittivity in a vacuum ($8.854 \times 10^{-12} \text{ Fm}^{-1}$) and A is the electrode area.

Results and Discussion

Figure 1(a) presents the XRD patterns of the BTS powder and ceramic, which were fabricated via the solid state reaction method with a calcination temperature of $1,200^\circ\text{C}$ for 2 h and a sintering temperature of $1,400^\circ\text{C}$ for 4 h. The BTS powder exhibited a pure perovskite phase structure, with no observed secondary phase. Figure 1(b) shows the 2θ angle between 35 - 50° to observe the key structural characteristics of the BTS samples. The BTS ceramic exhibited a phase coexistence between the orthorhombic and tetragonal phases, which corresponded with the Joint Committee on

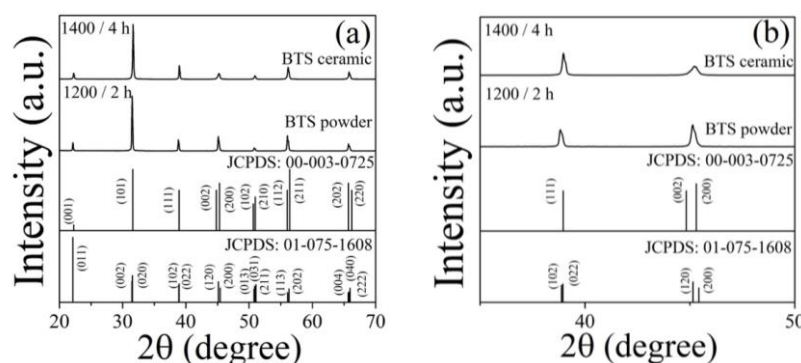


Figure 1. X-ray diffraction patterns of BTS powders and ceramics calcined at $1,200^\circ\text{C}$ and sintered at $1,400^\circ\text{C}$ and within a 2θ range of (a) 10 - 70° and (b) 35 - 50°

Powder Diffraction Standards (JCPDS) files no. 01-075-1608 and 00-003-0725, respectively. The results of the phase structure are the same as in previous work (Yao *et al.*, 2012).

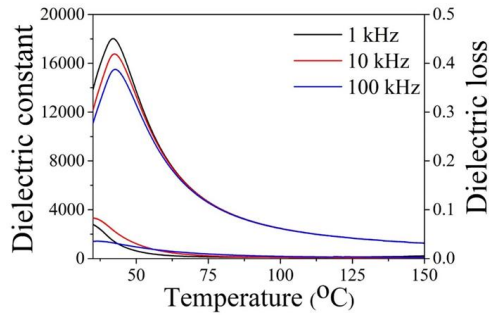


Figure 2. Temperature dependence of the dielectric constant of BTS ceramics sintered at 1,400°C

Figure 2 shows the temperature dependence of the dielectric constant (ϵ_r) and dielectric loss ($\tan \delta_r$) of the BTS ceramics measured at 1, 10, and 100 kHz in the temperature range of 35°C-150°C. It was observed that the BTS ceramics displayed a peak dielectric around the temperature of 42°C, indicating the transition from the tetragonal ferroelectric phase to the cubic paraelectric phase (T_C) (Liu *et al.*, 2017). The ϵ_r at room temperature was 13,843 and the highest dielectric constant at T_C (T_C) was 18,023. The $\tan \delta_r$ at room temperature and at T_C was 0.07 and 0.04, respectively.

Figure 3(a, b) displays the microstructure of the ceramics with 30 and 70 volume % BTS content, observed with the Scanning Electron Microscope (SEM), and Figure 3(c, d) shows the Energy Dispersive X-ray Spectrometer (EDS) analysis of the BTS/ACSA cement composite produced with 30 volume % of BTS ceramic. As the BTS content increased, the microstructure of the BTS/ACSA cement composite showed a higher amount of BTS, as seen in Figure 3(a, b). Figure 3(c, d) indicated that the primary elements in the BTS ceramic was Ba and Ti. Furthermore, Ca was identified as the main element in the cement portion. The EDS analysis for composites with 40-70 volume % of BTS content have a similar result as that of the 30 volume % sample (data not shown). All BTS/ACSA cement composites exhibited an interfacial transition zone (ITZ) between the BTS ceramic and the ACSA cement as shown in Figure 4. For 30, 40, and 50 volume % of BTS, as seen in Figure 4(a-c), it was found that the BTS ceramic and ACSA cement effectively bound together. For 60 volume % BTS content, small cracks were observed within the BTS ceramic phase. These cracks became more obvious when the BTS content increased to 70 volume %. Moreover, porosity slightly increased with increased BTS content, as illustrated in Figure 4(a-e).

The dielectric constant (ϵ_r) and dielectric loss ($\tan \delta_r$) of 0-3 BTS/ACSA cement composites with different BTS content were measured at a frequency of 1 kHz, as shown in Figure 5. It was found that the experimental results revealed a correlation between an increase in the volume of BTS in

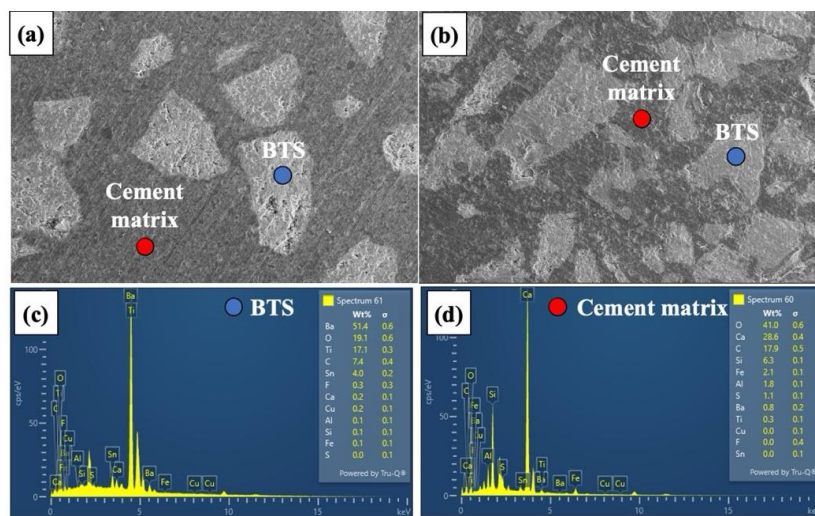


Figure 3. Microstructure of the BTS/ACSA cement composite with (a) 30 vol% and (b) 70 vol% of BTS and Energy-dispersive spectroscopy (EDS) analysis of 30 vol% of the BTS ceramic content (c) BTS ceramics phase and (d) cement matrix phase

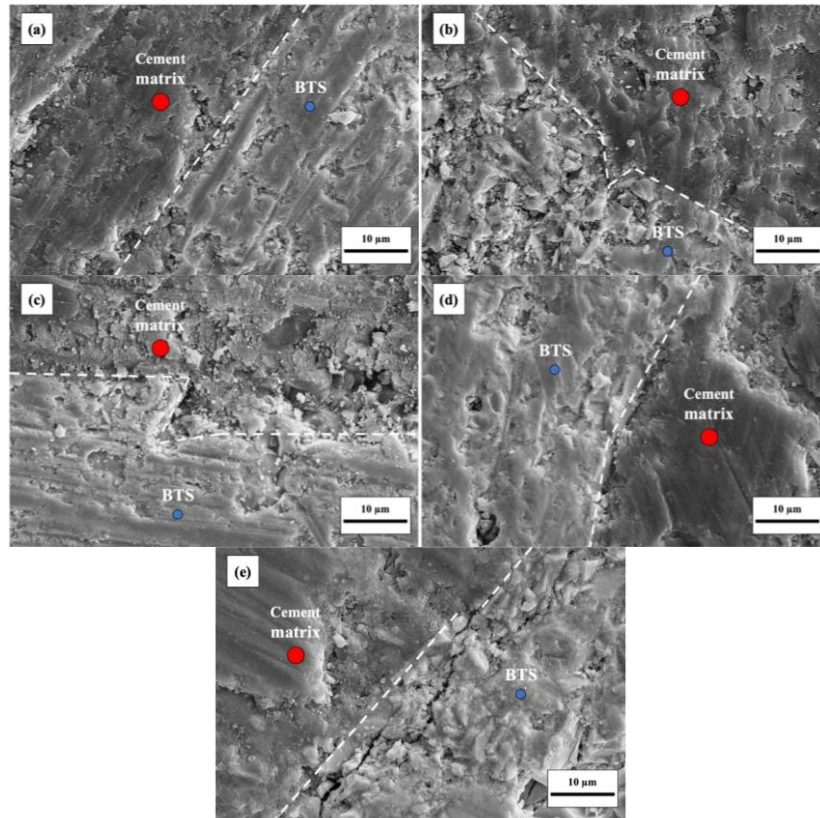


Figure 4. Microstructure of the BTS/ACSA cement composite at the ITZ with (a) 30 vol%, (b) 40 vol%, (c) 50 vol%, (d) 60 vol% and (e) 70 vol% of BTS; ● marks the BTS ceramic phase and ● marks the cement matrix

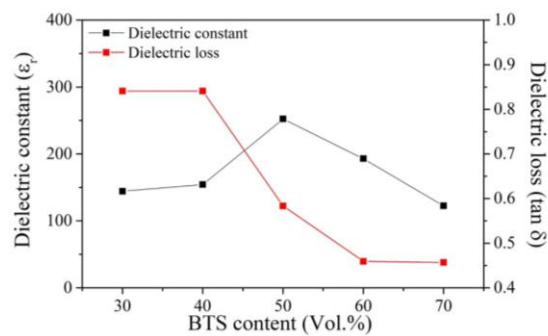


Figure 5. The dielectric constant (ϵ_r) and dielectric loss ($\tan \delta_r$) of BTS/ACSA cement composites measured at a frequency of 1 kHz

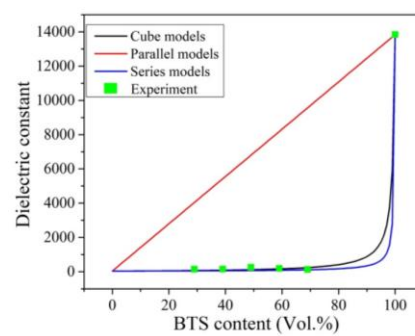


Figure 6. Dielectric constant values obtained from the experimental data compared with models of BTS/ACSA cement composites

the BTS/ACSA cement composite and an upward trend in the ϵ_r , up to a 50 volume % BTS content and then decreased with additional BTS. The decrease in ϵ_r was due to the increased number of cracks in the BTS/ACSA cement composites as seen in the SEM results. In the case of the composites with 30-50 volume % BTS content,

the increase in the dielectric content was a result of the combination of properties from the two phases (dielectric and cement) presented in the composite (Newnham, 1986). The $\tan \delta_r$ decreased as the BTS content increased. The $\tan \delta_r$ tended to decrease due to conduction ions (such as OH^- , Ca^{2+} , and Al^{3+}) in the cement matrix, which reduced the dielectric

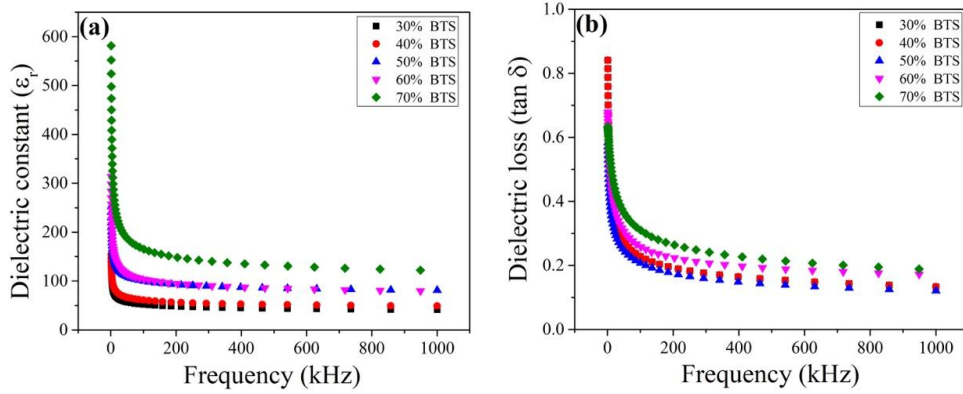


Figure 7. Dielectric properties as a function of frequency of BTS/ACSA cement composites with (a) Dielectric constant (ϵ_r) and (b) Dielectric loss ($\tan \delta_r$)

loss (Newnham *et al.*, 1980; Potong *et al.*, 2017). Figure 6 shows a comparison of the dielectric constant at room temperature using three models: 1) the parallel model, 2) the series model, and 3) the cubic model of composite materials. The parallel and series mixing models represent scenarios with alternating layers of the ceramic phase and cement phase, perpendicular and parallel to the applied field, respectively. The cubic model illustrates the characteristics of combining both parallel and series phases. The dielectric constant can be calculated using the following equations (Yoon *et al.*, 2003):

Parallel model; $\epsilon_c = V_1\epsilon_1 + V_2\epsilon_2$

Series model; $\frac{1}{\epsilon_c} = \frac{V_1}{\epsilon_1} + \frac{V_2}{\epsilon_2}$

Cubic model;

$$\epsilon_c = \frac{\epsilon_1 \cdot \epsilon_2}{(\epsilon_2 - \epsilon_1) \cdot V_1^{-1/3} + \epsilon_1 V_1^{-2/3}} + \epsilon_2 (1 - V_1^{-2/3})$$

where ϵ_1 is the dielectric constant of the BTS ceramic; ϵ_2 is the dielectric constant of the cement matrix, v_1 is the volume percentage of the BTS ceramic and v_2 is the volume percentage of the cement matrix. The results indicated that the BTS/ACSA cement composites had values similar to the ones predicted by the cubic model, suggesting that the BTS ceramic is well-mixed and distributed in a random pattern within the composite, similar to the characteristics of a cubic model composite (Yoon *et al.*, 2003).

The ϵ_r and $\tan \delta_r$ of 0-3 BTS/ACSA cement composites at different frequencies (1-1000 kHz) are shown in Figures 7(a) and 7(b), respectively. It was observed that, ϵ_r tended to decrease from 252 to 81 as the frequency increased from 1 kHz to 1,000 kHz at 50 volume % of BTS. In high frequency electric fields, the dipoles in the BTS/ACSA cement composites cannot reorient fast enough (Potong *et al.*, 2015). From Figure 7(b) it can be seen that $\tan \delta_r$ decreased at higher frequencies, dropping from 0.46 to 0.11 at 70% BTS ceramic content. The ϵ_r was higher, and $\tan \delta_r$ was lower when compared to the BT/Portland cement composite measured at a frequency of 1 kHz (Rianyoi *et al.*, 2011).

Conclusions

BaTi_{0.91}Sn_{0.09}O₃ - BTS ceramics were produced via the conventional solid state reaction method with a calcination temperature of 1,200°C for 2 h and a sintering temperature of 1,400°C for 4 h. The BTS powder and BTS ceramic had a perovskite structure with coexisting orthorhombic and tetragonal phases which had a dielectric constant (ϵ_r) at room temperature of 13,843 and at T_C of 18,023. All BTS/ACSA cement composites exhibited an interfacial transition zone (ITZ) between the BTS ceramic and ACSA with a slight increase in porosity as the BTS content increased. Effective binding was observed at 30-50 volume % BTS, resulting in the dielectric constant (ϵ_r), measured at 1 kHz of the BTS/ACSA cement composite, increasing with increased BTS ceramic. At a BTS ceramic content of 60 and 70 volumes % a decrease in ϵ_r at 1 kHz was observed, caused by poor binding with cracking at the ITZ boundary in the BTS/ACSA cement

composites. The dielectric loss ($\tan \delta_r$) at 1 kHz decreased with increasing BTS content. The dielectric constant and dielectric loss at various frequencies (1-1,000 kHz) decreased with increasing BTS content.

Acknowledgements

This research was financially supported by Naresuan University and the National Science, Research, and Innovation Fund (NSRF) [R2567B078]. The authors thank the Department of Physics, Faculty of Science, Naresuan University for their supporting facilities. Thanks, are also given to Asst. Prof. Dr. Kyle V. Lopin for his help in editing the manuscript.

References

- Alarcon-Ruiz, L., Platret, G., Massieu, E., and Ehrlicher, A. (2005). The use of thermal analysis in assessing the effect of temperature on a cement paste. *Cement and Concrete Research*, 35(3):609–613. <https://doi.org/10.1016/j.cemconres.2004.06.015>
- Bullerjahn, F., Schmitt, D., and Ben Haha, M. (2014). Effect of raw mix design and of clinkering process on the formation and mineralogical composition of (ternesite) belite calcium sulfoaluminate ferrite clinker. *Cement and Concrete Research*, 59:87–95. <https://doi.org/10.1016/j.cemconres.2014.02.004>
- Chaipanich, A. and Nochaiya, T. (2010). Thermal analysis and microstructure of Portland cement-fly ash-silica fume pastes. *Journal of Thermal Analysis and Calorimetry*, 99(2):487–493. <https://doi.org/10.1007/s10973-009-0403-y>
- Chomyen, P., Potong, R., Rianyo, R., Ngamjarurojana, A., Chindaprasit, P., and Chaipanich, A. (2018). Microstructure, dielectric and piezoelectric properties of 0-3 lead-free barium zirconate titanate ceramic-Portland fly ash cement composites. *Ceramics International*, 44(1), 76–82. <https://doi.org/10.1016/j.ceramint.2017.09.112>
- Dong, B. and Li, Z. (2005). Cement-based piezoelectric ceramic smart composites. *Composites Science and Technology*, 65(9):1363–1369. <https://doi.org/10.1016/j.compscitech.2004.12.006>
- El-Alfi, E.A. and Gado, R.A. (2016). Preparation of calcium sulfoaluminate-belite cement from marble sludge waste. *Construction and Building Materials*, 113:764–772. <https://doi.org/10.1016/j.conbuildmat.2016.03.103>
- Hargis, C.W., Telesca, A., and Monteiro, P.J.M. (2014). Calcium sulfoaluminate (ye'elimite) hydration in the presence of gypsum, calcite, and vaterite. *Cement and Concrete Research*, 65:15–20. <https://doi.org/10.1016/j.cemconres.2014.07.004>
- Jaitanong, N., Yimnirun, R., and Chaipanich, A. (2011). Effect of Compressive Stress on the Ferroelectric Hysteresis Behavior in 0-3 PMN-PT/Cement Composites. *Ferroelectrics Letters Section*, 38(1–3):11–17. <https://doi.org/10.1080/07315171.2011.570174>
- Juenger, M.C.G., Winnefeld, F., Provis, J.L., and Ideker, J.H. (2011). Advances in alternative cementitious binders. *Cement and Concrete Research*, 41(12):1232–1243. <https://doi.org/10.1016/j.cemconres.2010.11.012>
- Li, Z., Zhang, D., and Wu, K. (2001). Cement matrix 2-2 piezoelectric composite-Part 1: Sensory effect. *Materials and Structures*, 34:506–512. <https://doi.org/10.1617/13669>
- Li, Z., Zhang, D., and Wu, K. (2002). Cement-based 0-3 piezoelectric composites. *Journal of the American Ceramic Society*, 85(2):305–312. <https://doi.org/10.1111/j.1151-2916.2002.tb00089.x>
- Li, Z.-X., Yang, X.-M., and Li, Z. (2006). Application of cement-based piezoelectric sensors for monitoring traffic flows. *Journal of Transportation Engineering*, 132(7):565–573. [https://doi.org/10.1061/\(ASCE\)0733-947X\(2006\)132:7\(565\)](https://doi.org/10.1061/(ASCE)0733-947X(2006)132:7(565))
- Liu, W., Wang, J., Ke, X., and Li S. (2017). Large piezoelectric performance of Sn-doped BaTiO₃ ceramics deviating from quadruple point. *Journal of Alloys and Compounds*, 712:1–6. <https://doi.org/10.1016/j.jallcom.2017.04.013>
- Newnham, R.E. (1986). Composite electroceramics. *Ferroelectrics*, 68(1):1–32. <https://doi.org/10.1080/00150198608238734>
- Newnham, R.E., Bowen, L.J., Klinker, K.A., and Cross, L.E. (1980). Composite piezoelectric transducers. *Materials and Design*, 2(2):93–106. [https://doi.org/10.1016/0261-3069\(80\)90019-9](https://doi.org/10.1016/0261-3069(80)90019-9)
- Nochaiya, T., Wongkeo, W., Pimraksa, K., and Chaipanich, A. (2010). Microstructural, physical, and thermal analyses of Portland cement-fly ash-calcium hydroxide blended pastes. *Journal of Thermal Analysis and Calorimetry*, 100(1):101–108. <https://doi.org/10.1007/s10973-009-0491-8>
- Potong, R., Rianyo, R., Jarupoom, P., Pengpat, K., and Chaipanich, A. (2009). Effect of particle size on the dielectric properties of sodium potassium niobate-Portland cement composites. *Ferroelectrics Letters Section*, 36(3–4):76–81. <https://doi.org/10.1080/07315170903152748>
- Potong, R., Rianyo, R., Ngamjarurojana, A., and Chaipanich, A. (2015). Acoustic and dielectric properties of 0-3 bismuth sodium titanate-bismuth potassium titanate-barium titanate/cement composites. *Ferroelectrics Letters Section*, 43(4–6):77–84. <https://doi.org/10.1080/07315171.2016.1210469>
- Potong, R., Rianyo, R., Ngamjarurojana, A., and Chaipanich, A. (2017). Microstructure and performance of 1-3 connectivity environmentally friendly lead-free BNBK-Portland cement composites. *Materials Research Bulletin*, 90:59–65. <https://doi.org/10.1016/j.materresbull.2017.02.008>
- Rianyo, R., Potong, R., Jaitanong, N., Yimnirun, R., and Chaipanich, A. (2011). Dielectric, ferroelectric and piezoelectric properties of 0-3 barium titanate-Portland cement composites. *Applied Physics A*, 104:661–666. <https://doi.org/10.1007/s00339-011-6307-2>
- Rungchit, A., Poon, C.S., Chindaprasit, P., and Pimraksa, K. (2017). Synthesis of low-temperature calcium sulfoaluminate-belite cements from industrial wastes and their hydration: Comparative studies between lignite fly ash and bottom ash. *Cement and Concrete Composites*, 83:10–19. <https://doi.org/10.1016/j.cemconcomp.2017.06.013>
- Santos, J.A., Sanches, A.O., Akasaki, J.L., Tashima, M.M., Longo, E., and Malmonge, J.A. (2020). Influence of PZT insertion on Portland cement curing process and piezoelectric properties of 0-3 cement-based composites by impedance spectroscopy. *Construction and Building Materials*, 238:117675. <https://doi.org/10.1016/j.conbuildmat.2019.117675>
- Tiantong, P., Bongkarn, T., Rianyo, R., and Julphunthong, P. (2022). Fabrication and characterisation of 0-3 KNLNTS piezoelectric ceramic/alite calcium sulfoaluminate cement composites. *Journal of Materials Research and Technology*, 19:1563–1572. <https://doi.org/10.1016/j.jmrt.2022.05.136>

- Wongkeo, W., Thongsanitgarn, P., Chindaprasirt, P., and Chaipanich, A. (2013). Thermogravimetry of ternary cement blends. *Journal of Thermal Analysis and Calorimetry*, 113(3):1079–1087. <https://doi.org/10.1007/s10973-013-3017-3>
- Xin, C., Dongyu, X., Lingchao, L., Shifeng, H., and Minhua, J. (2010). Performance investigation of 1-3 piezoelectric ceramic–cement composite. *Materials Chemistry and Physics*, 121(1–2):63–69. <https://doi.org/10.1016/j.matchemphys.2009.12.045>
- Yao, Y., Zhou, C., Lv, D., Wang, D., Wu, H., Yang Y., and Ren, X. (). Large piezoelectricity and dielectric permittivity in BaTiO₃-xBaSnO₃ system: The role of phase coexisting. *EPL, A Letters Journal Exploring the Frontiers of Physics*, 98(2):27008. <https://doi.org/10.1209/0295-5075/98/27008>
- Yoon, D.-H., Zhang, J., and Lee, B.I. (2003). Dielectric constant and mixing model of BaTiO₃ composite thick films. *Materials Research Bulletin*, 38(5):765-772. [https://doi.org/10.1016/S0025-5408\(03\)00075-8](https://doi.org/10.1016/S0025-5408(03)00075-8)