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Research Article

Properties of glass-ceramics foam based on granite dust-clay-maize cob composite as a sustainable building material

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ABSTRACT

In this study, samples of glass-ceramics foam were obtained from granite dust-clay-maize cob composite and chemical additives at low temperature. Effects of the addition of maize cob as the pore-forming agent as well as the chemical additives on the performance properties of the samples of the glass-ceramics foam were investigated. The result of the prepared glass-ceramics foam showed water absorption, apparent porosity, bulk density, compressive strength and thermal conductivity of 25.6–46.7%, 43.5–75%, 1.45–1.9 g/cm^3, 0.7–9.7 MPa and 0.11–0.53 W/m.K. respectively. The mechanical and thermo-physical properties as well as microstructural properties of the glass-ceramics foam synthesized in this study provide a feasible indicator that the material can be used in promoting green and sustainable buildings.

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1. INTRODUCTION

Glass-ceramics foam is a class of materials that possesses interesting properties including low density, good moisture absorption, low thermal insulation and high chemical resistance among others [1, 2]. Important applications of glass-ceramics foam as a sustainable material for promoting green buildings cannot be overemphasized. World over, there is an escalating need for energy-efficient building design through the use of climate responsive materials or passive cooling devices for wall insulation [3]. Glass-ceramics foam is advantageous over polymeric foams (such as polystyrene and polyurethane) for use in building/construction due to its non-flammability, flame resistance, chemically inertness and non-toxicity [4, 5]. Glass-ceramics foam can be obtained through different processing methods including: replica template, direct foaming method, partial sintering, sacrificial template, additive manufacturing [6] and freeze-drying method [7] among others. The simplest processing technique by far is by sacrificial template method which involves powder sintering with the incorporation of foaming agents [8]. Another interesting thing about this method lies in the fact that cellulosic wastes such as saw dust, banana leaves, walnut and Yaba mate among others have found useful application as pore-forming agent in the production of glass-ceramics foam rather than culminating into environmental pollution [9–12].

Several researches on fabrication of glass-ceramics foam are commonly based on the use of by-products of high tem-

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perature industrial activities including metallurgical slag, fly ash and waste glass among others [13–26]. However, in view of the limited resources of these pyrotechnical industrial wastes for mass production of value-added products, the raw material base route for production of glass-ceramics foam is relevant [27, 28]. Hence, using natural raw materials such as granite dust which are available in abundance and are suitable for the production of glass-ceramics foam is necessary [29]. Single-step sintering of glass-ceramics foam based on aluminosilicate rocks provides an energy-saving route that eliminates preliminary glass melting by making it possible to combine the formation of a glassy phase and its cellular structure in a single technological process [30]. In this respect, glass-ceramics foam have been prepared based on: siliceous rocks and thermonatrite ($Na_2CO_3{\cdot}H_2O$) [31], waste quartz sand and coal gangue [32], tripoli with the addition of microsilica (10–50 wt.%) and 45% NaOH [27], and diatomite and 40% NaOH [33] among others. Based on the foregoing, it is noteworthy that processing glass-ceramics foam from industrial and agricultural wastes does not only promote environmental sustainability but also provides a route for mass-production of value-added building materials at low cost.

[34, 35] observed that thermal insulation in buildings have not been massively adopted in developing countries such as Nigeria mostly due to cost issues among others. In order to channel a feasible path for the development of cost-effective thermal insulation materials in Nigeria, [36] has investigated into the possibility of developing porous ceramics from wastes using single-step sintering. This study makes an attempt to experiment on the possibility of obtaining glass-ceramics foam from cheap natural resources such as granite dust and ball clay using maize cob as pore-forming agent. Ball clay is richly available in millions of tonnes across each states within the six geopolitical spreads of the country [37]. According to National Bureau of Statistics, Nigeria produced 9.62 million tonnes of granite, 2.12 million tonnes of granite aggregates, 28, 420 tonnes of granite block and 3.39 million tonnes of granite dust in the 2018 fiscal year [38]. Annual maize production in Nigeria as at 2018 was over 10 million metric tonnes [39]. Based on these statistics, it is evident that granite dust and maize cob are available in abundance in the country. However, these wastes have not been fully utilized in Nigeria as at the time this research was conducted. While maize cob (or corn cob) has been employed as a pore-forming agent in the production of porous ceramics in previous studies [40, 41], this research is novel in that it synthesized glass-ceramics foam from granite dust-clay-maize cob composite with a mixture of NaOH and Na_2SiO_3, a combination of starting materials which have not been used in the production of glass-ceramics foam based on extant literature reviewed. Given that building contributes enormously to carbon emission and energy consumption, thermal insulation is a green building strategy that leads to energy efficiency, low cost and low maintenance [42, 43]. Green-building problem has been identified as a one of the major problems among the numerous difficulties the housing sector has suffered from the COVID-19 pandemic [44]. Therefore, this research investigated into the performance properties of glass-ceramics foam developed using locally sourced raw materials as well as easy ceramic fabrication technique with a view to providing additional documented procedures of synthesizing materials that promote green and energy efficient environment in developing countries.

2. MATERIALS AND METHODS

2.1 Raw Materials and Chemical reagents

The study used granite dust sourced from Dotmond Quarry, Ita-Ogbolu, Ondo State, Nigeria as the base raw material, ball clay obtained from Ire-Ekiti, Ekiti State, Nigeria as the binder, maize cob powder obtained from the Seed Department, Agricultural Development and Processing, Akure, Nigeria as the pore-forming agent and mixture of NaOH and Na_2SiO_3 as the sintering aid. The NaOH and Na_2SiO_3 used was supplied by Qualikems Fine Chemicals Pvt. Ltd. And May & Baker Ltd., Dagenham, England respectively. The NaOH pellets used has minimum assay of 98.9% and the Na_2SiO_3 used contains about 12% Na_2O, 30% SiO_2 and 58% water.

2.2 Preparation of Samples

The raw materials including granite dust, ball clay and maize cob were sun dried, oven dried, grinded and sieved. Granite dust, ball clay and maize cob were sieved through 300 μm, 300 μm and 425 μm British Standard sieve respectively. 10 M NaOH solution was prepared. Mixture of 10 M NaOH and Na_2SiO_3 was prepared in ratio 1:1. Formulation of samples involved the mixture of varying percentage by weight of granite dust, ball clay and maize cob up to 100 g with constant percentage by weight of the mixture of NaOH and Na_2SiO_3 in three different groupings as shown in Table 1. After this each of the formulated samples was thoroughly mixed, the homogenized compositions was poured into the mould of dimension 50 mm x 50 mm x 50 mm and was uniaxially pressed at 10 MPa. The pressed samples were dried in the electric oven at 110 °C for 6 hours and sintered in the gas kiln up to 850 °C for 3 hours and soaked for 2 hours.

2.3 Characterization

To obtain the chemical composition of the raw materials used in this study, X-ray Fluorescence (XRF) analysis was conducted using Skyray Instrument, Model: EDX3600B and Nikon SMZ745T Stereomicroscope was used to investigate the microstructural properties of the developed glass-ceramics foam sintered at 850 °C.

Table 1. Formulation of glass-ceramics foam samples

Samples grouping	Sample designation	Granite dust (g)	Ball clay (g)	Maize cob (g)	NaOH (cm^3)	Na_2SiO_3 (cm^3)
1	C_1	63	32	5	7.5	7.5
	C_2	60	30	10	7.5	7.5
	C_3	57	28	15	7.5	7.5
2	R_1	63	32	5	10	10
	R_2	60	30	10	10	10
	R_3	57	28	15	10	10
3	N_1	63	32	5	12.5	12.5
	N_2	60	30	10	12.5	12.5
	N_3	57	28	15	12.5	12.5

2.3.1 Water Absorption, Apparent Porosity and Bulk Density

The values of water absorption, apparent porosity and bulk density of the samples were measured using the Archimedes method according to ASTM C20-00 [45] and were calculated using equations (1), (2) and (3) respectively.

$$Water\ Absorption = W_2 - W_1 / W_1 \times 100\% \quad (1)$$

$$Apparent\ Porosity = W_2 - W_1 / W_2 - W_3 \quad (2)$$

$$Bulk\ density = W_1 / W_2 - W_3 \quad (3)$$

Where W_1, W_2 and W_3 are the sintered weight of sample, the soaked weight of the sample after boiling at 100 °C for 2 hours and the suspended weight of samples in water respectively.

2.3.2 Compressive Strength

A digital Instron Series 3369 compressive strength testing machine at a fixed crosshead speed of 10 mm min–1was used to measure the compressive strength of the produced glass-ceramics foam samples in accordance to ASTM C240-97 [46].

2.3.3 Thermal Conductivity

Thermal Conductivity test was carried out on the samples using a self-constructed Lee's Disc apparatus according to [47]. Thermal conductivity (k) was calculated using equation (4).

$$k = 2.303\ MC\delta\ [log\ (\theta_1 = Ts - T_1 / \theta_2 = Ts - T_2)] / A.\ \tau \quad (4)$$

where, k, M, C, δ, θ_1, θ_2, Ts, T_1, T_2, A and τ are thermal conductivity of the specimen, (W/m˚C), mass of water in conical flask (kg), specific heat capacity of water in conical flask (4200 J/kg˚C), thickness of sample (m), temperature of steam (˚C), initial temperature of water in the conical flask (˚C), final temperature of water in the conical flask (˚C), Area of sample (m^2) and time (s) respectively.

3. RESULTS AND DISCUSSION

3.1 Chemical Properties of the Starting Raw Materials

The result of XRF analysis as shown in Table 2 revealed that the granite dust used mainly contained silicon oxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) representing 59.72%, 12.82% and 11.29% respectively. Hence, granite dust is a suitable raw material for glassy phase as required for the production of glass-ceramics foam since it contains a considerable amount of SiO_2 which is generally known as glass former and Al_2O_3 which always serves as stabilizer in glass formation. Potassium oxide (K_2O) and calcium oxide (CaO) representing 5.74% and 5.67% of the granite dust sample respectively are other significant oxides suitable for glass production. K_2O serves as fluxing agent in glass production and CaO contributes to the crystallinity of a glass-based material. The ball clay used mainly contained SiO_2, Al_2O_3 and Fe_2O_3 representing 58.15%, 21.60% and 12.40% respectively. The ball clay shows a good quality of aluminosilicate material with iron oxide as the major impurity which is mostly responsible for the brown colouration in ball clay. The essence of using ball clay in this study is due to its plasticity so as to provide the required binding aid to granite dust (a non-plastic material) which is the main raw material for this study. However the presence of high amount of SiO_2 in the ball clay could have served as an additional aid in providing glassy base material for the study. The maize cob used mainly contained SiO_2, Al_2O_3,

Table 2. Chemical compositions of the raw materials used in this study (wt %)

Oxide	Granite dust	Ball clay	Maize cob
Al_2O_3	12.82	21.60	13.79
SiO_2	59.72	58.15	27.75
P_2O_5	0.44	0.21	1.42
SO_3	0.82	0.71	6.37
K_2O	5.74	2.30	9.28
CaO	5.67	0.15	7.19
TiO_2	0.35	0.81	–
Fe_2O_3	11.29	12.40	10.88
SnO_2	–	–	4.66
Sb_2O_3	–	–	4.74
LOI	3.15	3.67	13.92

Table 3. Chemical properties of some main raw materials used in previous studies compared to granite dust used in this study

Main raw material	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	Na_2O	MgO	P_2O_5	SO_3
Coal Fly Ash [14]	35.42	39.40	2.63	10.04	0.40	–	–	0.217	4.62
TTP Slag [48]	57.5	23.0	10.8	1.9	3.6	–	–	–	–
Glass Cullet [49]	66.0	3.0	0.3	11.2	3.3	12.2	3.7	–	–
Granite Dust*	59.72	12.82	11.29	5.67	5.74	–	–	0.44	0.82

*: Present study.

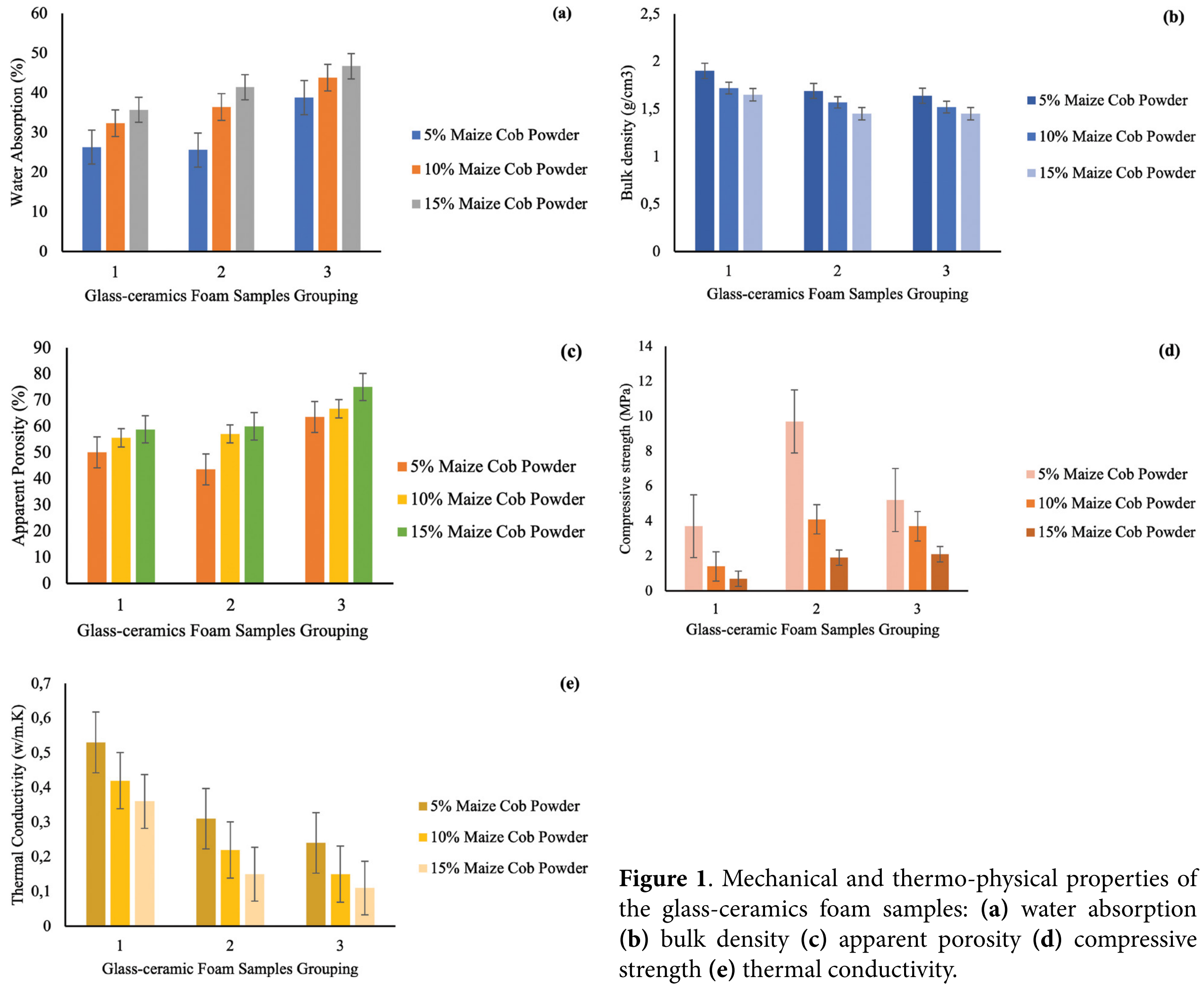

Figure 1. Mechanical and thermo-physical properties of the glass-ceramics foam samples: **(a)** water absorption **(b)** bulk density **(c)** apparent porosity **(d)** compressive strength **(e)** thermal conductivity.

Fe_2O_3, K_2O and CaO representing 27.75%, 13.79% and 10.88%, 9.28% and 7.19% respectively and these are important oxides in glass and ceramic production.

The comparative analysis of chemical properties of some main raw materials used in previous studies to granite dust used in this study are as shown in Table 3. While Coal fly ash, TTP slag and glass cullet are industrial wastes of high temperature processes, granite dust is an industrial waste of the quarry industry which has not been subjected to any initial heat treatment; however, it can be observed from Table 3 that the chemical composition of granite dust used in this study matches favourably with some of the wastes that have undergone heat treatment used in previous studies for the synthesis of glass-ceramics foam. This reveals its suitability for the fabrication of glass-ceramics foam via single-step sintering route which was achieved in this study by using chemical additives (NaOH and Na_2SiO_3) as sintering aid.

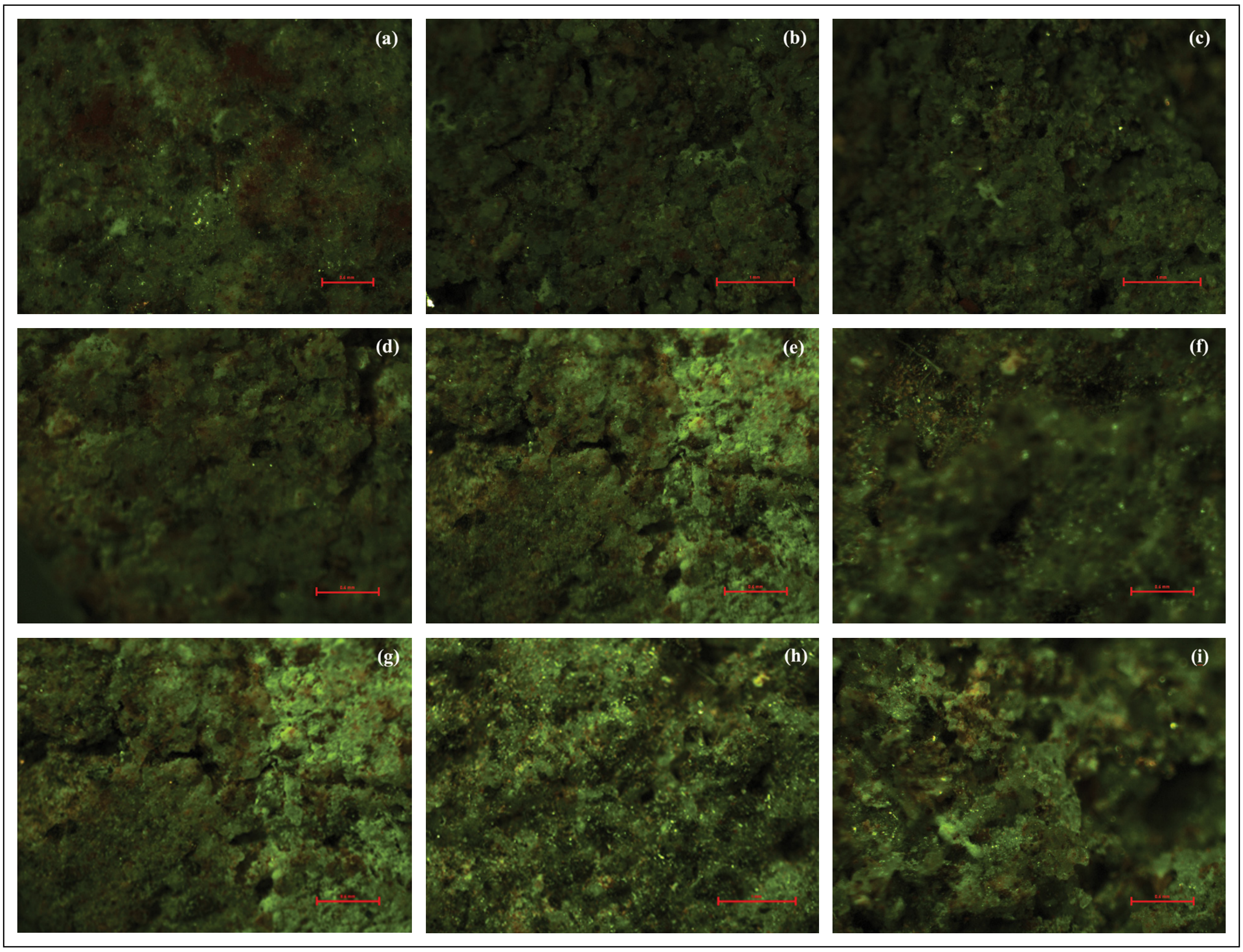

Figure 2. Stereomicroscope images of the porous glass-ceramic samples: **(a)** C_1 **(b)** C_2 **(c)** C_3 **(d)** R_1 **(e)** R_2 **(f)** R_3 **(g)** N_1 **(h)** N_2 **(i)** N_3.

3.2 Mechanical and Thermo-Physical Properties

The trend in the mechanical and thermo-physical properties of the glass-ceramics foam synthesized in this study are presented. Figure 1a–c show the result of water absorption, bulk density and apparent porosity of the glass-ceramic foam samples at varying addition of pore-forming agent and chemical additives. It is observed that the samples sintered at 850 °C, water absorption increased gradually from C_1-C_3, R_1-R_3 and N_1-N_3 respectively; apparent porosity increased gradually from C_1-C_3, R_1-R_3 and N_1-N_3 respectively while the values of bulk density decreased gradually from C_1-C_3, R_1-R_3 and N_1-N_3 respectively with the increasing amount of maize cob powder and the chemical additives used.

Figure 1d showed that the compressive strength of the samples decrease linearly from C_1-C_3, R_1-R_3 and N_1-N_3 respectively with the increasing amount of maize cob powder and chemical additives used. Figure 1e showed that the thermal conductivity values of the samples decrease from C_1-C_3, R_1-R_3 and N_1-N_3 respectively with the increasing amount of maize cob powder and chemical additives used. These trends of properties of the glass-ceramics foam samples with respect to increase in pore-forming agent are in agreement with [50] and also justifies the use of alkali-based chemical additives to activate an enhanced sintering process [4, 51].

3.3 Microstructure

The microstructural properties of the developed porous glass-ceramic samples sintered at 850 °C are as shown in Figures 2a–i. The micrographs show different morphological structures of various degrees of agglomeration and porosity. The porosity is observed to increase with the increase in percentage of the alkali-based chemical additives and maize cob powder added, leading to decrease in compressive strength, increase in water absorption as well as increase in coefficient of thermal conductivity in each of the sample groupings 1–3, that is, from C_1-C_3, R_1-R_3 and N_1-N_3 respectively of the samples is observable. The pore size distribution is heterogeneous. The developed glass-ceramics foam exhibit open-celled morphology which is advantageous to its effectiveness not only in thermal insulation but also in acoustic insulation in the sense it provides an absorbent surface as large as possible that favours sound absorption [52].

4. CONCLUSION

The results obtained in this study in compliance with ASTM standards revealed that one-step sintering method can be used to develop glass-ceramics foam with the addition of appropriate chemical reagents at a temperature as low as 850 °C. The use of waste resources in this research encourages wastes remediation which is an important means of promoting environmental sustainability. The different degrees of agglomeration and porosity of the samples as revealed by the micrographs confirm the results of their varying physical, mechanical and thermal properties. The properties of the material synthesized in this study indicate that it can be suitably used in promoting green and sustainable buildings. While this research focused on evaluating the effect of varying the amount of the mixtures of NaOH and Na_2SiO_3 on the properties of glass-ceramic foams sintered at a constant temperature, further research should explore the effect of different sintering temperature ranges and other types of chemical reagents than the ones used in this study on the properties of glass-ceramic foams obtained from granite dust-clay-maize cob composite.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The author declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

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