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Thermal and acoustic properties of sustainable structural lightweight aggregate rubberized concrete

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ABSTRACT

This study investigated the effect crumb rubber recycled from wasted tires on properties of structural lightweight aggregate concrete (LWAC). Two types of concrete were tested: control LWAC and rubberized lightweight aggregate concrete (RLWAC). The control LWAC consisted of cement, fine aggregate (river sand), and lightweight coarse aggregate (porous aggregates). For the RLWAC, the fine aggregate was replaced by crumb rubber at the rate of 10, 20, 30, 40, and 50% by volume. The water to cement ratio for both concrete types was set at 0.35. The experiment series consisted of density (ASTM C567), compressive strength (ASTM C39), flexural strength (ASTM C78), thermal conductivity (ASTM C518), and sound absorption coefficient (ISO 10534-2). Results showed the decrease in density of about 10%, compressive strength of 21.4%, and flexural strength of 35.4% with the increasing crumb rubber replacement ratio up to 50%. For thermal and sound properties, the increasing crumb rubber content of up to 50% improved the thermal insulation of concrete, as seen by the decrease in thermal conductivity by about 14.6%. RLWAC also exhibited superior sound insulating properties to LWAC as seen by higher sound absorption coefficient over the working sound frequency range. In order to satisfy the requirements of ASTM C330 and ACI 318, the optimum crumb rubber replacement was recommended at less than 10%.

1. Introduction

Thailand is responsible for about one-third of the world's rubber supply (about 4.3 million tons in 2015) [1]. This is the highest among the top ten natural rubber-producing countries [2]. In terms of consumption, about 85–90% of the rubber is exported and about 10–15% is locally used. About half of the local usage is utilized in the vehicle tires industry. Thailand also ranked no. 69 in the world on the number of vehicle per capita (206 vehicles per 1000 people) [3]. In 2016, the Department of Land Transport reported an accumulative of about 37 million registered land vehicles [4]. Under the assumption that each vehicle changes their tires every two years, this roughly yields about 75 million abandoned tires annually. With this kind of number, waste management related to abandoned tires has become a challenging problem not only in Thailand but also worldwide.

According to UNEP, the end of service life for most wasted tires can undergo three possible solutions [5]: energy recover, recovering or recycling, and landfill. In terms of recovering and recycling, waste tires can be ground into crumb rubber or recycled into reclaimed rubber. Crumb rubbers are used commonly in applications like rubber-modified asphaltic road, sport fields/tracks overlay, playground rubber tiles, etc.

In the case of concrete applications, rubberized concrete normally exhibited excellent toughness and impact energy absorption [6–8]. This was due to its high elasticity, which enabled crumb rubber to bridge across and slow down crack propagation similar to short fibers [9]. However, the addition of crumb rubber appeared to adversely affect the mechanical properties significantly, as seen by the reduction of strength with the increasing crumb rubber content. Several researchers [10–17] also reported similar findings related to rubberized concrete. This drawback limits the application of rubberized concrete to low strength or nonstructural components such as partition walls, drainages, pedestrian blocks, etc.

For nonstructural components like partition walls where strength is not a major concern, the focus is directly toward other properties such as

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thermal insulation and sound absorption. In order to improve these properties, supplementary materials with specific properties related to thermal and sound improvement are often mixed with cement materials. For example, the use of materials with high latent heat such as phase change materials (PMC) are often used to improve thermal storage of concrete [18–30]. For crumb rubber, its low density and high specific heat characteristics undoubtedly provide positive effect to both thermal and sound properties of nonstructural lightweight concrete [31–33]. Some wastes from recycle plastering or ceramic can also be utilized as a sustainable repairing material and properties enhancement agent for circular economy [34–36].

Since rubberized concrete is poor in mechanical properties, most research related to rubberized concrete are focused and moved toward the non-structural purpose. Still, there is a small number of investigations that focused on utilizing rubberized concrete for structural purposes [37,38]. This study also aimed to add more information on the existing body of knowledge related to structural rubberized concrete, especially, on the thermal and sound properties. The control LWAC was made of Portland cement, sand and LWA with w/c ratio of 0.35. For RLWAC, the crumb rubbers retrieved from recycled abandoned tires were used to replace fine aggregates at the rate of 10–50% by volume. The experimental program consisted of 2 parts. Part 1 is to investigate properties requirement for structural lightweight concrete in according to ACI 318 [39] and ASTM C330 [40] which included unit weight, compressive strength, and flexural tests. Part 2 is to further investigate the thermal conductivity, and sound absorption coefficient related to RLWAC.

2. Research methodology

2.1. Materials

Materials used in this study consisted of Portland Cement Type 1 (C) with a specific gravity of 3.15 (ASTM C150). Fine aggregate was river sand (S) with a specific gravity of 2.65. For crumb rubber (CR), a commercial grade crumb rubber (CR) with specific gravity of 0.96 and absorption of 0.92% was used (Table 1). Lightweight aggregate (LG) was porous aggregates with unit weight of 732 kg/m^3 and absorption of 16% (Table 2). The gradation curves of all aggregates are shown in Fig. 1.

2.2. Mix proportion

The mix proportion of lightweight aggregate concrete (LWAC) was set at C:S:LG of 617:520:475 kg/m3 and water to cement (w/c) ratio of 0.35 (Table 3). For rubberized lightweight aggregate concrete (RLWAC), sand was replaced with crumb rubber at the rate of 10, 20, 30, 40, and 50% by volume (Table 3).

2.3. Specimen preparation

To prepare the test specimens, all raw materials were dry mixed in a pan mixer for 1–2 min before water was added. The mixing then continued for another 1–2 min. The specimens were prepared differently depending on the type of test. Cylindrical specimens with dimensions of 100 mm × 200 mm were prepared for the compressive strength test. The specimen was cast into 3 equal layers and each layer was compacted for 25 times by a steel rod. For the flexural strength test, beam specimens with dimensions of 100 × 100 × 350 mm were prepared. Each specimen was cast into 2 equal layers, and each layer was compacted with a steel rod for 60 times. For the thermal conductivity test, block specimens with dimensions of 200 × 200 × 5 cm were poured in one layer, compacted with a steel rod for 30 times, and then vibrated on a vibrating table for 1 min to remove air bubbles. All specimens were covered with plastic sheets to prevent water evaporation. After 24 h, the specimens were demolded, wrapped with a plastic sheet, and cured at room temperature for 28 days.

Table 1
Properties of crumb rubber.

Specification	Test Result
Average Bulk Specific Gravity (Oven Dry)	0.96
Average Bulk Specific Gravity (SSD)	0.97
Average Apparent Specific Gravity	0.97
Average Absorption (%)	0.92
Fineness Modulus (F.M.)	4.93

Table 2
Properties of lightweight aggregates.

Properties	Test Result
Unit weight	732 kg/m^3
Percent of voids aggregate	72%
Bulk specific gravity (Dry Basis)	1.08
Bulk specific gravity (SSD Basis)	1.25
Apparent specific gravity	1.30
Percent Absorption	16%

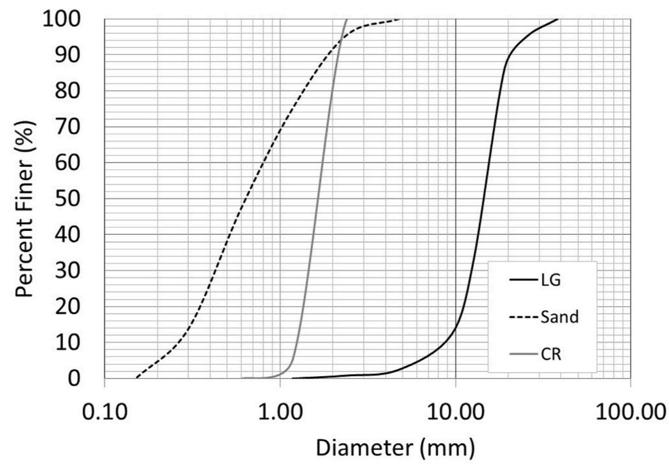

Fig. 1. Grading curve of aggregates.

Table 3
Mix proportion of LWAC and RLWAC.

Type of Concrete	Mix proportion (kg/m^3)				
	Cement (C)	Sand (S)	Lightweight aggregate (LG)	Water (W)	Crumb rubber (CR)
LWAC	614	520	475	215	–
10RLWAC	614	468	475	215	19
20RLWAC	614	416	475	215	38
30RLWAC	614	364	475	215	57
40RLWAC	614	312	475	215	76
50RLWAC	614	260	475	215	95

2.4. Experimental series

For structural lightweight aggregate concrete, there are two standards (ACI 318 and ASTM C330) involve in specifying property requirements as follows:

- ASTM C330 specifies density of structural lightweight concrete between 1120 and 1920 kg/m^3 and minimum compressive strength of 17 MPa.
- ACI 318 specifies density range in the range of 1440–1850 kg/m^3 and minimum compressive strength of 17.2 MPa.

- ASTM C330 specified minimum splitting tensile strength of 2 MPa.

In order to investigate the properties of RLWAC based on the requirement of both standards, a series of experiments were set as follows:

- Density of Lightweight Concrete (ASTM C567)
- Compressive Strength (ASTM C39)
- Flexural strength (ASTM C78)
- Thermal Conductivity (ASTM C518)
- Sound absorption coefficient (ISO 10534-2)

For some basic tests such as ASTM C567, ASTM C39, and ASTM C78, the test procedures are quite well known, therefore the detail of those tests are not presented. The details of the thermal and sound properties are described as follows.

2.4.1. Thermal conductivity

In this study, the thermal conductivity (λ) amount was conducted at a temperature of 30 °C. The test setup began with placing a specimen between two controlled heat plates. The specimen was then heated up to a matching temperature. Once the constant heat flux was obtained, the temperature on one of the hot plates was set to a new target temperature, this allowed the heat to transfer from one side to the other through the specimen. After the steady state was attained, the test was then terminated and the total heat needed for the specimen to reach the temperature target was measured. The thermal conductivity coefficient can be calculated using Eq. (1).

$$\lambda_T = q.\left(\frac{L}{\Delta T}\right) \tag{1a}$$

where λ_T is thermal conductivity at any temperature (W/m · K), q is heat flux (W/m^2), L is the distance between the heat plates (m) and ΔT is temperature difference across the specimen (K).

2.4.2. Sound absorption coefficient

The sound absorption coefficient (α) was tested using a circular impedance tube with diameter of 29 mm and two microphones in according to ISO 10534-2. The circular specimens with dia-290 × 500 mm were prepared. Measurements were carried out according to the standing wave method where a loudspeaker set up a sound field in a tube terminated by the sample. When the standing waves were produced in the tube, the ratio between the maximum and minimum sound pressure was measured. The absorption coefficient of the sample for zero-degree incident sound wave was then calculated from the measured data.

3. Results and discussion

3.1. Density

The results showed that the density of RLWAC decreased with the increasing rubber content. As seen in Fig. 1, the maximum density of 1765 kg/m^3 was found in LWAC. The lowest density of 1588 kg/m^3 was observed in 50RLWAC. The decrease in the unit weight was partly because crumb rubber has lower specific gravity than fine aggregate. Hence, by replacing fine aggregates with crumb rubber particles, the density decreased gradually. Another reason could be the formation of voids due to the addition of crumb rubber particle [41].

Based on the obtained results, all specimens exhibited density between 1588 and 1765 kg/m^3 which are in the range of 1440–1850 kg/m^3 according to ACI 318 and 1120 and 1920 kg/m^3 according to ASTM C330 requirements (Fig. 2). Therefore, they are considered satisfying both standards in term of density.

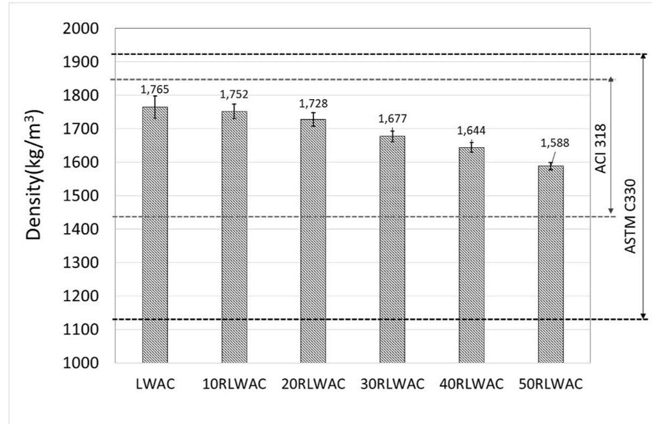

Fig. 2. Density of LWAC and RLWAC

3.2. Compressive strength

Fig.3 shows the results on compressive strength test. Results indicated that the replacement of fine aggregate with crumb rubber from 0% to 50% resulted in the decrease in compressive strength from 19.69 MPa (LWAC) to 15.48 MPa (50RLWAC). The reduction in strength was due to the lower strength of crumb rubber as compared to that of fine aggregates (river sand). By replacing strong materials with weaker materials, the strength dropped gradually. Another reason could come from the increasing void content in concrete due to accumulation of crumb rubber around aggregates [41]. Gupta et al. [42] indicated that the addition of rubber ash generated more voids in concrete which caused the compressive strength to decrease.

The compressive strength was observed in the range of 15.48–19.69 MPa. According to the ACI and ASTM standards for structural lightweight aggregate concrete, the minimum compressive strength requirement is 17–17.2 MPa, therefore only LWAC, 10RLWAC, and 20RLWAC exhibited sufficient compressive strength both standards in term of strength.

3.3. Tensile strength

Using the test results from the flexural test, the modulus of rupture (MOR) can be obtained as shown in Table 4. Similar to the case of compressive strength, the MOR was also found to decrease with the increasing crumb rubber content. The MOR of LWC and LWCR were observed in the range of 2.20 and 3.41 MPa and the decreasing was in the range of 19–55% with the replacement ratio of 10–50%.

According to the ASTM C330 standard, the minimum splitting tensile

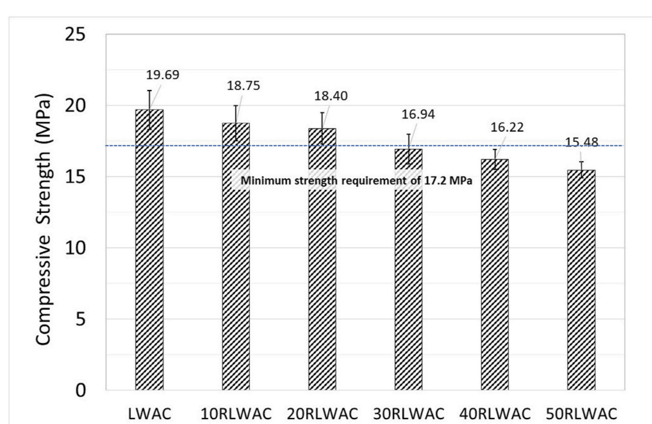

Fig. 3. Compressive strength of LWAC and RLWAC.

Table 4
Modulus of Rupture and approximated splitting tensile strength.

Type	Bending Load (kN)	MOR (MPa)	App. STS (MPa)	Decision
LWAC	11.37	3.41	2.39	Pass
10RLWAC	9.55	2.87	2.01	Pass
20RLWAC	8.63	2.59	1.81	Not pass
30RLWAC	8.28	2.48	1.74	Not pass
40RLWAC	7.60	2.28	1.60	Not pass
50RLWAC	7.34	2.20	1.54	Not pass

Note: Conversion factor from MOR to STS = 0.70.
ASTM C330 requirement for structural LWAC = 2 MPa.

strength requirement is 2 MPa. In order to convert the MOR into splitting tensile strength (STS), a conversion factor in introduced. Based on the literature review, Olanike [43] investigated the relationship between MOR and STS of recycled lightweight aggregate concrete and concluded that the STS is lower than the MOR by about 60–80%. Troxell et al. [44] also suggested the relationship between the STS and MOR of plain concrete between 50 and 75%. In this study, the conversion factor of 0.70 was adapted which is based on the average value from Olanike [43] study on recycled lightweight aggregate concrete. The converting STS results are also given in Table 4.

From the results in Table 4, the allowable crumb rubber replacement rate to pass the requirement for tensile strength was at 10% by volume of sand.

3.4. Optimum crumb rubber content

Considering the density, all RLWAC exhibited density within the allowable range of both ASTM and ACI standards. In the case of compressive and STS, the allowable crumb rubber replacement was limited to 20% and 10% by volume, respectively. Therefore, it can be concluded that the optimum crumb rubber replacement rate to pass all requirements for structural lightweight aggregate rubberized concrete was at 10%. It must be noted here that the optimum crumb rubber content can be varied from one study to the others depending on the several factors. For example, Williams and Partheeban [45] observed an optimum crumb rubber content of 12% when used in replacing coarse aggregate. Senin et al. [46] used rubber ash to replace sand at the rate of 3–9%. The rubberized concrete was subjected to flexural load and the optimum replacement rate was found at 3% by volume of sand. Güneyisi et al. [47] observed the allowable replacement rate of crumb rubber at 25% by volume in rubberized concrete mixed with silica fume to obtain the compressive strength from 16 to 32 MPa.

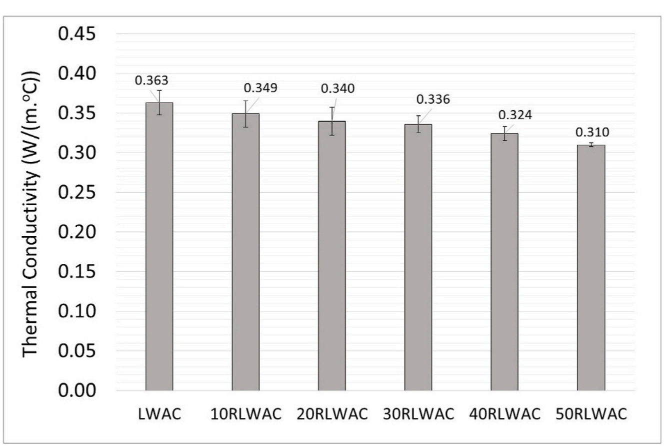

Fig. 4. Thermal conductivity (λ) of LWAC and RLWAC.

3.5. Thermal conductivity

The results on the thermal conductivity (λ) of LWAC and RLWAC are shown in Fig. 4. The range of λ of 0.310 and 0.363 W/(m.°C) were observed in this study. The λ had a tendency to decrease with the increasing crumb rubber content. The highest λ of 0.363 W/(m.°C) was observed in LWAC. The lowest λ of 0.310 W/(m.°C) was observed in 50RLWAC. The decrease in λ was partly due to the reduction of density with the increasing crumb rubber content due to smaller density of crumb rubber as compared to sand and the formation of internal voids [41,42]. Another reason could be the high specific heat of crumb rubber which allows the rubberized concrete to exhibit higher insulating properties and lower thermal conductivity [31,33]. Results from Saleh et al. [48] reported the thermal conductivity coefficient values of concrete containing Nano-silica in the range of 0.5–0.92 W/m °C which are higher than that of rubberized concrete found in this study.

3.6. Sound absorption coefficient

The sound absorption coefficient (α) was tested using a circular impedance tube with diameter of 29 mm in according to ISO 10534-2. According to the standards, the working frequency of a circular impedance tube is limited by an upper (f_U) and lower frequencies (f_L) which affected by test setup configurations such as tube diameter, microphone distance, sound velocity, etc.

Assuming the velocity of sound in air at sea level and temperature of 298.15 K (25 °C) (c_0) = 346.2 m/s, d = 29 mm and s = 30 mm, the upper (f_{U1}, f_{U2}) and lower frequencies (f_L) of the impedance tube can be calculated using Eqs. (2) and (3) and shown in Table 5.

$$f_L < f < f_U \tag{1b}$$

$$f_L < K_L \frac{c_0}{s} \tag{2}$$

$$f_{U1} < K_{U1} \frac{c_0}{d} \tag{3}$$

$$f_{U2} < K_{U2} \frac{c_0}{s} \tag{4}$$

$$c_0 = 343.2\sqrt{t/293}\ (\mathrm{m/s}) \tag{5}$$

Based on the calculation results in Table 5, the lower (f_L) and upper (f_U) frequencies of the impedance tube are limited to 577 and 5193 Hz, respectively. The test results on the sound absorption coefficient (α) within the working frequency range are shown in Fig. 5. At a frequency range lower than 1000 Hz, the α of all specimens are in a similar range. Although the RLWAC exhibited higher α than LWAC, the differences were not as significant. For example, at frequency of 800 Hz, the α of LWAC, 10RLWAC, 20RLWAC, 30RLWAC, 40RLWAC, and 50RLWAC were observed at 0.025, 0.035, 0.038, 0.043, 0.050, and 0.055, respectively.

At a frequency higher than 1000 Hz, the α was found to increase with the increasing frequency. This indicates the strong effect of frequency

Table 5
Upper and lower sound frequencies limitation [49–51].

Parameters		Unit	Note
K_L	0.05	–	ISO 10534-2
K_{U1}	0.58	–	ISO 10534-2
K_{U2}	0.45	–	ISO 10534-2
c_0	346,203	mm/s	Sound velocity in air at 25 °C
d	29	mm	Inner diameter of the tube
s	30	mm	Distance between microphones
Frequency limitation			
f_L	577	Hz	
f_{U1}	6924	Hz	
f_{U2}	5193	Hz	

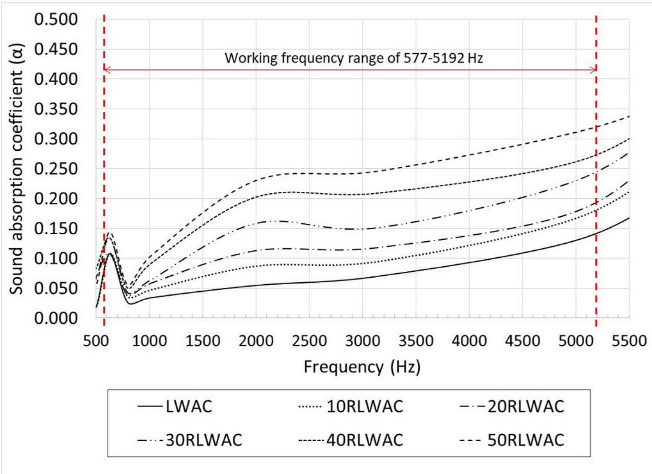

Fig. 5. Sound absorption coefficient (α) of LWAC and RLWAC within working frequency range.

over the α [52]. When considering the same frequency, the RLWAC exhibited higher α than LWAC in every replacement ratio and every frequency. The α also increased with the increasing crumb rubber replacement ratio. For example, at 5000 Hz, the α of LWAC, 10RLWAC, 20RLWAC, 30RLWAC, 40RLWAC, and 50RLWAC were observed at 0.130, 0.167, 0.178, 0.230, 0.261, and 0.311, respectively.

The increase in sound absorption coefficient of RLWAC indicated that RLWAC is better in sound insulation than LWAC. Theoretically, when sound waves meet the surface of a material, part of the sound is reflected, part of it passes through, and the rest is transferred to the material. As the sound waves transfer to the material by entering the pores system inside the material, the friction resistance between the air molecules and the pores rises. This converts sound energy into heat energy, which is absorbed by the material [52]. As mentioned earlier, the addition of crumb rubber leads to the increase in void content of rubberized concrete [41,42]. The higher void content creates more friction and causes sound waves to be converted into sound energy and absorbed by the voids.

4. Conclusions

Both thermal and sound properties including some mechanical properties of rubberized structural lightweight concrete have been successfully investigated.

In terms of density, the replacement of crumb rubber over sand caused the density to decrease due to the lower specific gravity of crumb rubber and the formation of internal voids, which led to the degradation of mechanical properties. Both compressive and flexural strengths were found to decrease with the increasing crumb rubber content. The allowable crumb rubber replacement ratio to pass the requirements for structural LWAC of both ASTM C330 an ACI 318 standards was observed at 10% by volume of sand.

The increasing crumb rubber content also led to an improvement in both thermal and sound insulation properties. The decrease in thermal conductivity coefficient (λ) indicated the ability of RLWAC to slow down the rate of heat transfer which contributed directly to the high specific heat capacity of crumb rubber and the increasing void content. In terms of sound absorption coefficient (α), the increasing α was the direct effect of the lower specific gravity of rubber and formation of voids in the microstructure.

At the optimum replacement rate (10%), the RLWAC exhibited density of 1752 kg/m^3, compressive strength of 18.75, splitting tensile strength of 2.01 MPa, thermal conductivity coefficient of 0.349 W/(m.^{o}C), and sound absorption coefficient between 0.108 and 0.167 (depending on the frequency).

Credit Author Statement

Phattharachai Pongsopha: Main Investigation, Formal analysis, Piti Sukontasukkul: Supervision, Conceptualization, Resources, Writing – review & editing, Hexin Zhang: Validation, Writing – review & editing, Suchart Limkatanyu: Validation, Resources, Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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