Engineering Journal issn: 0125-8281

Article

Development and PCA Evaluation of Lunar Mortar Compositions from Lunar Simulant and Potato-Based Materials

Sutatta Tayadhammadhat[1,a], **Theingi Nwe**[2,3,b], **Supan Yodyingyong**[4], **Wares Chancharoen**[3,c,*], **and Sarinya Paisarnsombat**[1,d,**]

1 Department of Earth Sciences, Faculty of Science, Kasetsart University, 50 Ngamwongwan Road, Lad Yao, Chatuchak, Bangkok 10900, Thailand
2 Department of Mechanical Engineering, Naypyitaw State Polytechnic University, Thirimandhain Junction, Pubbathiri Township, Naypyitaw 15014, Myanmar
3 Laboratory of Artificial Intelligence and Innovation in Medicine (AIIM), Princess Srisavangavadhana Faculty of Medicine, Chulabhorn Royal Academy, 906 Kamphaeng Phet 6 Rd., Talat Bang Khen, Lak Si, Bangkok 10210, Thailand
4 Institute for Innovative Learning, Mahidol University, Phuttamonthon Sai 4 Road, Salaya, Nakhon Pathom 73170, Thailand

E-mail: [a]Sutatta.tay@ku.th, [b]shwenwe13@gmail.com, [c,*]wares.cha@cra.ac.th (Co-corresponding author), [d,**]sarinya.pai@ku.ac.th (Corresponding author)

Abstract. Space activities have taken another step, particularly on the Moon, where the establishment of a human exploration base has garnered interest from many space agencies. One of the challenges lies in constructing shelter and accommodation using locally available resources. This study investigates the lunar mortar compositions using Thailand lunar regolith simulants and potato-based materials, including potato starch and fibers, as potential binding agents. Extensive experiments optimized the mortar formulation by varying the ratios of Thailand lunar simulant (TLS-01), potato starch, and fresh/fermented potato fibers. Compressive strength tests evaluated the effects of fiber reinforcement, TLS-01 percentage, potato starch, and heat treatment. Microstructural analysis via SEM revealed the internal structure and cohesion. Principal Component Analysis (PCA) identified major influencing variables on compressive strength and their correlations. The LC-FrF-3 sample, with TLS-01 (39.47%), potato fresh fiber (7.9%), and freezing (-10°C), exhibited maximum 0.65 MPa compressive strength. SEM showed specimens with dense cohesion and reduced voids, such as LC-FrF-3, had better strength. PCA highlighted 'TLS-01', 'Potato starch', 'Heat', and 'Freeze' as the most significant influencing variables. This research demonstrates the potential of lunar regolith simulants and potato-based materials for developing suitable lunar mortar for construction, contributing to in-situ resource utilization for space exploration.

Keywords: Lunar mortar, lunar regolith simulant, potato starch, potato fiber.

ENGINEERING JOURNAL Volume 29 Issue 2
Received 4 June 2024
Accepted 18 February 2024
Published 28 February 2024
Online at https://engj.org/
DOI:10.4186/ej.2025.29.2.81

1. Introduction

The Apollo missions, which achieved the historic milestone of landing humans on the Moon, created exceptional prospects for space exploration and scientific progress. One of the main challenges in establishing long-term human settlements on the Moon is the development of buildings and infrastructure that can sustain continuous lunar exploration. The establishment of a permanent human presence on the Moon and Mars is the focus of planning by NASA and the ESA, with an emphasis on utilizing in-situ resources for construction on Mars and the Moon [1], [2].

Transporting construction materials from Earth to the lunar surface poses a challenging logistical and economic obstacle because of the high costs and complexities of space transportation. Researchers and space agencies are exploring in-situ resource utilization (ISRU) as a solution to the limitations of transporting construction resources from Earth. This approach involves using the resources available on the Moon to produce the necessary construction materials, thereby facilitating the construction of buildings on the lunar surface. By incorporating ISRU, the need for transporting building resources from Earth can be reduced, ensuring cost-effectiveness and sustainability in lunar development efforts [3].

The lunar regolith, the loose soil and rock fragments covering the Moon's surface, is a possible supply of raw materials for the production of concrete and other construction materials [4]. By using lunar regolith, the requirement for transporting large quantities of resources from Earth can be minimized, thus decreasing the overall cost and complexity of lunar missions.

Previous research efforts have focused on creating lunar regolith-based concrete by partially or totally substituting typical aggregates, such as gravel and sand, with synthetic lunar regolith simulants [5], [6]. These experiments aimed to study the feasibility and properties of concrete mixtures adapted for lunar construction. Researchers have also investigated the application of biologically produced binding agents, such as plant stem fibers and starch, to enhance the strength and durability of construction materials [7]. These bio-based additives offer potential advantages in terms of sustainability and resource availability on the Moon.

Novel approaches have been investigated, including the production of extraterrestrial regolith biocomposites (ERBs), which blend lunar regolith with human serum albumin (HSA), a plasma protein that can be recovered from human body fluids such as blood, sweat, or tears [8]. These bio-based additives present potential benefits in terms of sustainability and resource availability on the Moon.

Another innovative process involves solidifying lunar regolith particles by reacting them with alcohol and an accelerator in a controlled environment, resulting in solid composite material blocks [9]. This method aims to produce solid structures directly from the lunar regolith without the need for additional binding agents. The current research explores an alternative strategy by producing lunar concrete using lunar regolith simulant and geopolymer, a type of inorganic aluminosilicate polymer that can be manufactured from natural resources such as fly ash or slag [10], [11]. Geopolymers offer potential advantages in terms of mechanical properties, durability, and suitability for lunar construction. Lunar mortar derived from lunar regolith simulants shows great promise for lunar construction materials [12]. Additionally, advancements in additive manufacturing technology, specifically photopolymerization methods, have enabled the successful creation of high-strength structures using lunar regolith simulants [13].

However, previous studies have not thoroughly investigated the use of agricultural waste, specifically potato starch and fibers, as binding agents in combination with lunar regolith simulants for lunar mortar development [14]. The research gap lies in the lack of systematic evaluation of the effects of varying ratios and quantities of these components on the mechanical properties and formation process of lunar mortar [15]. Additionally, there has not been extensive study on the influence of water content, a crucial element for practical application on the Moon [16].

To address this research gap, this study aims to develop lunar mortar compositions using agricultural waste, specifically potato starch and fibers, as binding agents, and the Thailand Lunar Simulant (TLS-01) as the primary aggregate [17]. This research uses a systematic experimental approach to optimize the mortar formulation by thoroughly evaluating the effects of varying the ratios and quantities of the components, including the lunar regolith simulant, potato starch, and potato fibers, both in their fresh and fermented states. A major part of the research is to examine the effect of water content on the formation process and the consequent compressive strength mechanical properties of the lunar concrete, given the restrictions on water availability on the Moon.

The study explores the relationship between the lunar regolith simulant and potato fibers on strength and workability, essential for optimizing mortar formulas for lunar construction. The mechanical properties, especially the compressive strength, are examined to determine their potential for practical uses on the lunar surface. Principal Component Analysis (PCA) is applied as a multivariate statistical tool to identify the important variables influencing the mortar properties and to study the interactions among these variables.

2. Materials and Methods

2.1. Materials

The fundamental materials used in the development of lunar mortar compositions in this study were lunar regolith simulant, potato starch, and potato fibers. These materials were carefully selected and prepared to mimic the in-situ resources available on the lunar surface and to serve as potential binding agents for the mortar formulations. Figure 1 display a scanning electron microscope (SEM) image of the Thailand Lunar Simulant (TLS-01) used in this study. The image displays a collection of irregularly shaped particles of varying sizes, closely resembling the diverse particle size distribution found in lunar soil. Table 1 describes the chemical composition content and units (weight percent) of the Thailand lunar simulant (TLS-01).

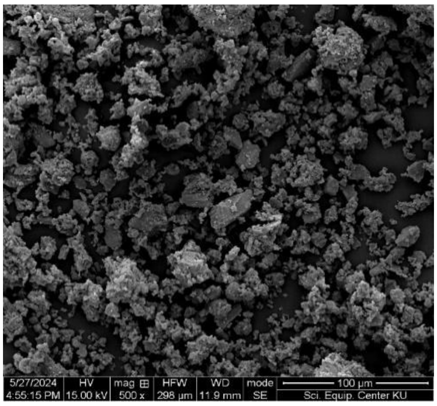


Fig. 1. The SEM image of TLS-01 illustrates the diverse range of particle sizes and shapes.

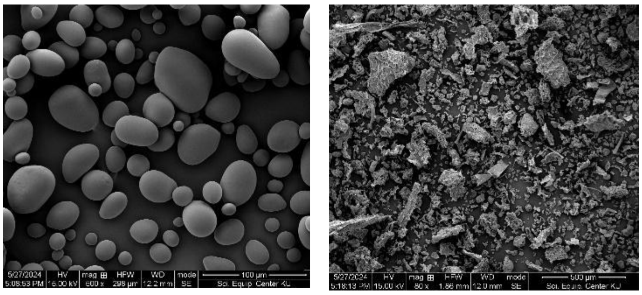
Table 1. Chemical Composition of TLS-01 Simulant (wt%)[17].

Chemical composition	Content (wt%)
SiO_2	44.6
$Na_2O + K_2O$	6.43
MgO	12.26
Al_2O_3	15.04
CaO	9.57
TiO_2	2.68
FeO_{Total}	7.92

This research aims to investigate a binder that can replace cement in mortar without relying on chemicals. As a result, we are investigating a binder made from commonly available bioproducts that can be produced in large quantities and serve as a food source for humans. This brings us to potatoes. When mixed with water, the starch in potatoes becomes a viscous substance, which is usually used to thicken ingredients in food and thus improve its texture. This particular property reflects its ability to be mortar.

Moreover, potato stems and leaves are also high in cellulose, which is the major component of plant fibers. These plant fibers can be utilized as reinforcement in mortar to provide it strength and a better load-carrying capability. Because of its minute size and fibrous character, the fiber functions as a reinforcement material that distributes the stress throughout the mortar, making it more resistant to impact. Natural fibers, such bamboo, reeds, and jute, minimize concrete cracking. Therefore, we would expect the potato fibers to have comparable qualities as other natural fibers to decrease mortar cracking from drying out and temperature variations.

Figure 2(a) shows the SEM image of potato starch, which is granular structured by spherical particles of varied size; the surface morphology of the starch granules is fairly smooth. Figure 2(b) depicts a SEM image of potato fibers with their fibrous and elongated shape. The rough, irregular surface texture of the fibers promotes the mechanical interlocking and adhesion within the concrete matrix, therefore enhancing the overall strength and reinforcing impact of the composite material.



(a) (b)

Fig. 2. The SEM images of (a) potato starch granules and (b) potato fiber (fresh).

2.2. Experimental Procedures

It is crucial to correctly prepare the samples to create lunar mortar mixtures suitable for construction on the Moon. The following sections discuss the experimental procedures implemented to assess the suitability and effectiveness of the materials used in the research.

2.2.1. Sample preparation

Preparing binders and accurately simulating lunar regolith are critical steps in the process of creating lunar mortar for use in lunar construction. This section addresses the structured processes used to make the Thailand Lunar Simulant (TLS-01), which is an essential part of modeling lunar regolith. It also describes the preparation of potato starch and fiber, used as binders in the lunar mortar matrix.

Thailand Lunar Simulant (TLS-01): Basalt rock, chosen for its similarity to lunar regolith based on findings from the Apollo missions [17], is size-reduced using a Los Angeles Abrasion machine (WF 51500, Wykeham Farrance, England). The rock is ground to reach a particle size range of approximately 0.3 - 0.075 mm and subsequently separated using sieves with mesh sizes No. 20, 50, 100, and 200. This process ensures the uniformity and desirable grain size distribution needed for simulating lunar soil properties. The Los Angeles machine and the size-separated TLS-01 are crucial for mimicking the characteristics of lunar soil for later experimentation (Fig. 3).

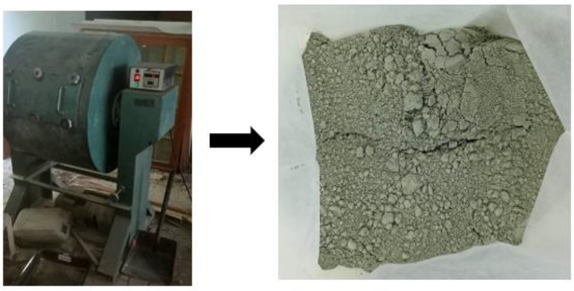


Fig. 3. The Los Angeles machine and Size-separated TLS-01.

Potato Starch: Potato starch, obtained from Ngao, Thoeng, Chiang Rai, is a key component in lunar mortar. It is prepared through two methods: instant potato starch and homemade potato starch. The potatoes are cleaned, peeled, and grated, then ground using a grinder (Optiblend AW-9, Moulinex, Indonesia). The grated potatoes are placed in water for 24 hours to allow the starch to separate. The water is drained, and the starch is rinsed to remove impurities. It is then spread on a clean pan and dried for an additional 24 hours at a controlled relative humidity of 60–70% to eliminate any residual moisture. Once dry, the starch is stored in an airtight container for future use, ensuring it is ready for incorporation into the mortar mixture (Fig. 4).

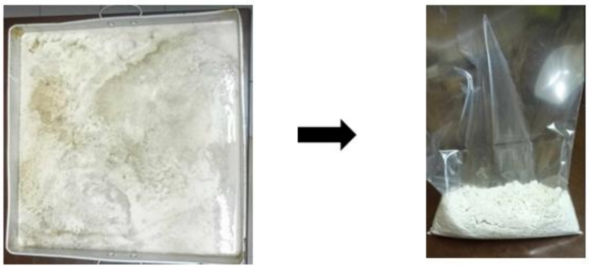


Fig. 4. Dry the settled starch to completely dry.

Potato Fiber: Two types of potato fiber, fresh and fermented, were prepared to investigate their unique properties and potential contributions to the lunar mortar matrix. For fermented fiber, potato fiber is placed in a container with water and left at a temperature of 35 – 40 °C for 5 days to initiate the fermentation process. Following fermentation, the fibers were dried for a period of 7 days to remove any excess moisture. Throughout the drying process, the relative humidity was carefully maintained within the range of 60–70%. Both fresh and fermented fiber then undergo centrifugation to achieve a particle size range of approximately 1 – 10 mm (Fig. 5). This controlled particle size range ensures the uniform distribution and effective incorporation of the fibers within the mortar matrix.

Fig. 5. Grind fibers in a grinder.

To obtain accurate and significant data for the creation of lunar mortar formulas specifically for lunar construction, great care must be taken in the preparation of these components. The systematic processes presented in this section ensure the appropriateness and effectiveness of the materials used in the study, permitting precise assessment and enhancement of the lunar mortar characteristics for lunar applications.

2.2.2. Mortar formulation and mixing

The formulation and mixing of lunar mortar are critical steps in developing construction materials adapted for lunar construction. In this study, various formulations were investigated to develop the mixture composition and processing parameters through a stepwise approach.

Step I: Base formulation: The initial mortar formulation involved combining clean water, potato starch, and the Thailand Lunar Simulant (TLS-01). The ingredients were thoroughly mixed to ensure a homogeneous distribution. Fiber reinforcement was incorporated by adding potato fibers (fresh or fermented) to the mixture after the initial mixing of the other components. After that, the mixture was poured into cube molds and placed in a freezer for three days at -10 °C to initiate the curing process. Subsequently, the samples were removed from the freezer and incubated for five days while being wrapped in a damp cloth to maintain moisture levels.

Step II: Water Content Optimization Formulation: To investigate the effect of water content on the mortar formulation, the initial formula was adjusted by reducing the amount of water used. The samples were placed in an incubator at 50 °C for 3 h, allowing for partial dehydration. Following the incubation period, the samples were transferred to a freezer for three days and then incubated outside while wrapped in a damp cloth for five days.

Step III: Lunar Regolith Simulant and Fiber Ratio: Building upon the insights gained from the previous phases, the formula was further adjusted by increasing the proportion of the TLS-01. Additionally, the water content was adjusted to accommodate varying fiber contents, enabling a comparative analysis between fresh and fermented potato fibers. The samples were left to cure for 24 h before being placed in a freezer for 3 h. Subsequently,

DOI:10.4186/ej.2025.29.2.81

they were incubated outside, wrapped in a damp cloth, for five days.

Figure 6 shows the three steps of the lunar mortar experimentation process, providing a visual representation of the research's step-by-step method. Table 2 summarizes the lunar mortar formulations with varying amounts of TLS-01, potato starch, fiber types (fresh or fermented), and curing conditions (heat, freeze, and dry durations) investigated in the study. Table 2 provides a comprehensive overview of the different sample formulations, enabling a systematic investigation of the influence of these variables on the mortar's properties.

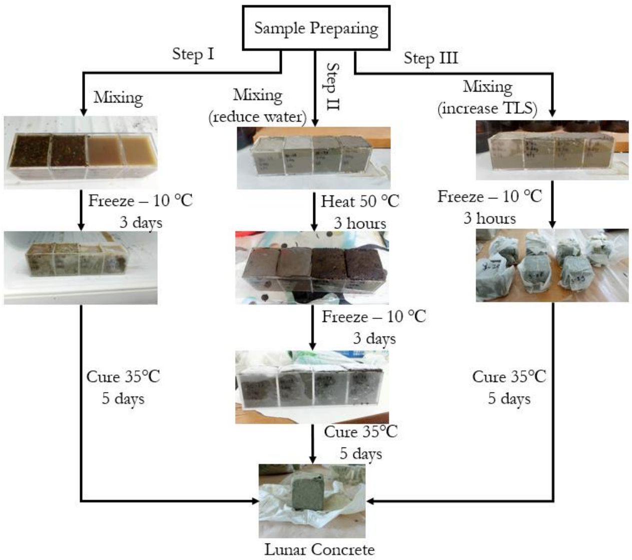


Fig. 6. The process of the lunar mortar experimentation in all 3 steps.

2.3. Compressive Strength Testing

Testing for compressive strength was conducted in accordance with industry standards to assess the mechanical properties of the lunar mortar created utilizing lunar simulants. The unloading of hollow mortar blocks was conducted according to the instructions specified in TIS 58-2533 [18], using a Universal Compressive Strength Testing Machine (UTM, Maximum load cell 20 ton, Chun Yen, China), The loading rate was maintained at 0.5 mm/min throughout the test and was calibrated according to the ASTM C109/C109M standard to ensure measurement accuracy. Before starting the studies, a control specimen with a known compressive strength was tested to verify performance.

Before conducting tests, cubic specimens of lunar mortar were created with dimensions (50 × 50 × 53 mm) as required by industrial standards. The prepared mortar specimens were then positioned within the compression testing machine, which is equipped with two steel plates, one rigid and one movable. After placing the sample in the testing machine, a load was applied constantly along the sample's longitudinal axis when the specimen was carefully aligned within the compression plates (Fig. 7). The specimen was subjected to a steady increase in axial load by the compressive testing machine at a specific rate, measured in newtons per second (N/s), until the sample failed. During the loading process, the maximum load and related deformation were recorded, which is vital for compressive strength analysis.

The compressive strength (fc) of the mortar specimens was determined using the formula:

$$\mathrm{fc} = \frac{P}{A} \tag{1}$$

where f_c indicates the compressive strength measured in MPa, P represents the applied force exerted during testing, measured in N, and A is the cross-sectional area of the sample, measured in mm².

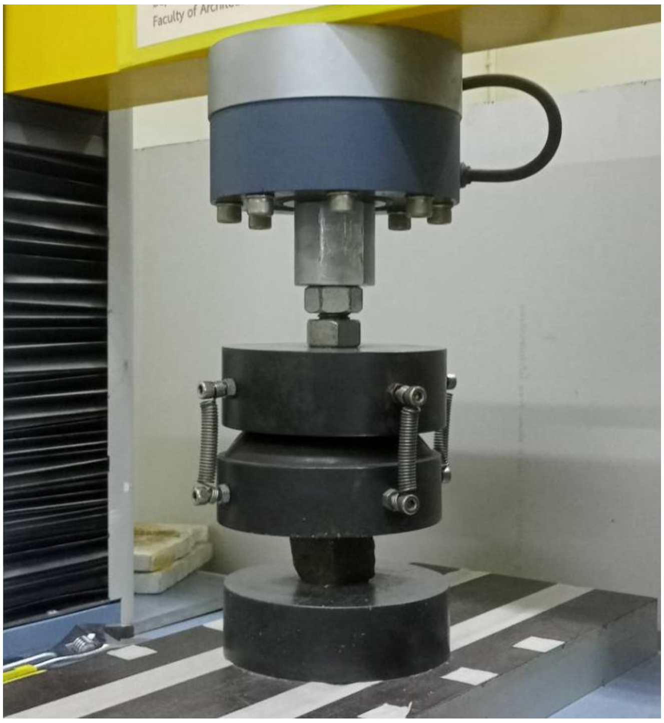


Fig. 7. Testing the compressive strength of lunar mortar sample by using Universal Compressive Strength Testing Machine.

2.4 Data Analysis Utilization Principal Component Analysis (PCA)

PCA was utilized in this study to examine the correlation between various lunar mortar formulation parameters and curing conditions that affect the mechanical properties of lunar mortar compressive strength (STR). Since PCA effectively performs data dimensionality reduction while retaining most of the significant patterns of variability, the method is selected to meet the objectives of the study in identifying critical factors affecting compressive strength. Unlike regression, which emphasizes prediction and clustering focuses on the process of grouping, PCA provides a way of analyzing variable contributions and their interactions [19]. The input data matrix consisted of rows representing the several mortar formulations, with variations in the levels of TLS-01, potato starch, fiber types (fresh/fermented), and curing conditions (heat, freeze, dry). The columns represented the mortar composition characteristics and the duration of curing (Table 2). The dataset used for PCA in this study was complete, with no missing values. If some were to be found, one would have considered mean imputation or expectation-maximization methods for consistency and reliability of the analysis.

Before performing PCA, the data was preprocessed using mean centering and scaling to prevent variables with higher numeric ranges from disproportionately affecting the analysis. Subsequently, PCA was performed using MATLAB's built-in functions.

The principal components (PC_i) were obtained by projecting the centered data (Xj) onto the eigenvectors of the covariance matrix (vi) [20], [21]:

$$PC_i = Xj \times vi \quad (2)$$

Principal component loadings, indicating the variable contributions to each PC, and scores, representing the observations in the new PC space, were calculated. The number of PCs retained was determined based on the cumulative explained variance [22]. Based on the PCA scores and variable loadings, key formulation parameters influencing the mortar compressive characteristics and correlated variations were identified.

Table 2. Lunar mortar Formulations with Varying TLS-01 (Thailand lunar simulant), Potato Starch, Fiber Types, and Curing Conditions.

Step	Sample Name	TLS -01 (kg)	Potato starch (kg)	Potato fiber type	Potato fiber (kg)	Water (kg)	Heat (h)	Freeze (h)	Dry (h)	STR (MPa)
1	LC-1	0.08	0.06	-	0	0.14	0	72	120	0.15
1	LC-FeF	0.08	0.06	Fermented	0.024	0.14	0	72	120	0.36
2	LC-1W	0.08	0.06	-	0	0.07	3	72	120	0.02
2	LC-2W	0.08	0.08	-	0	0.07	3	72	120	0.06
2	LC-FeF-1W	0.08	0.08	Fermented	0.024	0.07	3	72	120	0.23
2	LC-FeF-2W	0.08	0.06	Fermented	0.024	0.04	3	72	120	0.14
2	LC-FeF-3W	0.08	0.08	Fermented	0.024	0.04	3	72	120	0.24
3	LC-2	0.12	0.06	-	0	0.07	0	3	120	0.13
3	LC-FrF-1	0.12	0.06	Fresh	0.008	0.08	0	3	120	0.32
3	LC-FrF-2	0.12	0.06	Fresh	0.016	0.09	0	3	120	0.19
3	LC-FrF-3	0.12	0.06	Fresh	0.024	0.1	0	3	120	0.65
3	LC-FeF-1	0.12	0.06	Fermented	0.008	0.08	0	3	120	0.25
3	LC-FeF-2	0.12	0.06	Fermented	0.016	0.09	0	3	120	0.24
3	LC-FeF-3	0.12	0.06	Fermented	0.024	0.1	0	3	120	0.52

3. Result and Discussion

3.1. Compressive Strength Analysis

The compressive strength of the lunar mortar samples derived from lunar simulants was evaluated after 5 days of curing (Table 3). The maximum compressive strength of 0.65 MPa was achieved by the LC-FrF-3 sample, whereas the LC-1W sample exhibited the minimum compressive strength of 0.02 MPa.

Fiber content significantly impacts the compressive strength of the mortar; reducing the water content and increasing the fiber content results in higher compressive strength. It was observed that mortar has higher strength with a fiber content of 7.9%. These findings indicate that the compressive strength of the lunar mortar is significantly influenced by fiber reinforcement, the proportions of lunar regolith simulant (TLS-01), potato starch used in the mixture, and heat treatment.

Table 3. Compressive strength values of Lunar mortar samples.

Sample Group	Sample Name	Compressive Strength (MPa)
Step I	LC-1	0.15
	LC-FeF	0.36
Step II	LC-1W	0.02
	LC-2W	0.06
	LC-FeF-1W	0.23
	LC-FeF-2W	0.14
	LC-FeF-3W	0.24
Step III	LC-2	0.13
	LC-FrF-1	0.32
	LC-FrF-2	0.19
	LC-FrF-3	0.65
	LC-FeF-1	0.25
	LC-FeF-2	0.24
	LC-FeF-3	0.52

3.2. Microstructural Analysis

The microstructural characteristics of the lunar mortar samples were analyzed using scanning electron microscopy (SEM), showing how different factors affect internal structure and cohesiveness. A total of 14 samples were examined, and the images presented are representative of the typical micro-structural characteristics observed within each sample group. These images were selected to accurately reflect the most common features identified across the analyzed specimens. The SEM image of the LC-1 sample (Fig. 8(a)) showed internal structural voids caused by the larger particle size of potato starch compared to TLS-01. As a result, the mortar specimen has low compressive strength, with values that could not be measured.

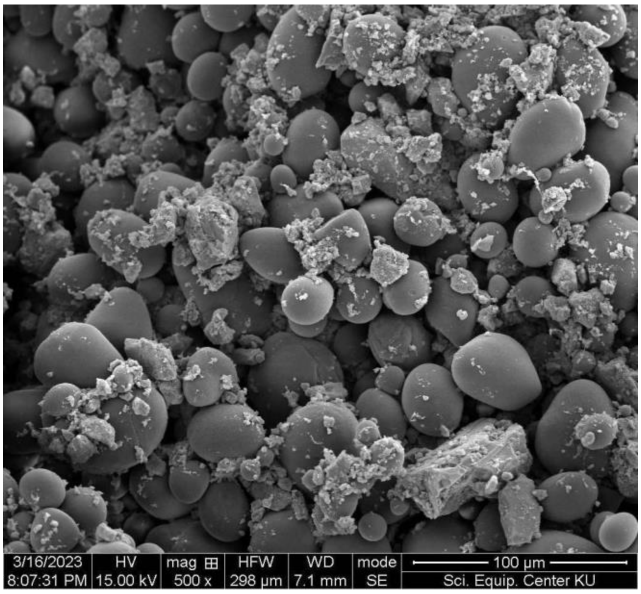
Heating the sample causes the potato starch to expand and crack, resulting in poor cohesion between the potato starch, TLS-01 aggregates, and fibers, leading to widespread voids throughout the structure and low compressive strength, as shown in the LC-FeF-3W sample (Fig. 8(b)).

The LC-FrF-3 sample (Fig. 8(c)) exhibited dense cohesion with reduced size and quantity of voids compared to samples that did not undergo heat treatment and had a higher amount of lunar simulant aggregates in the mortar. This dense cohesion resulted in higher compressive strength.

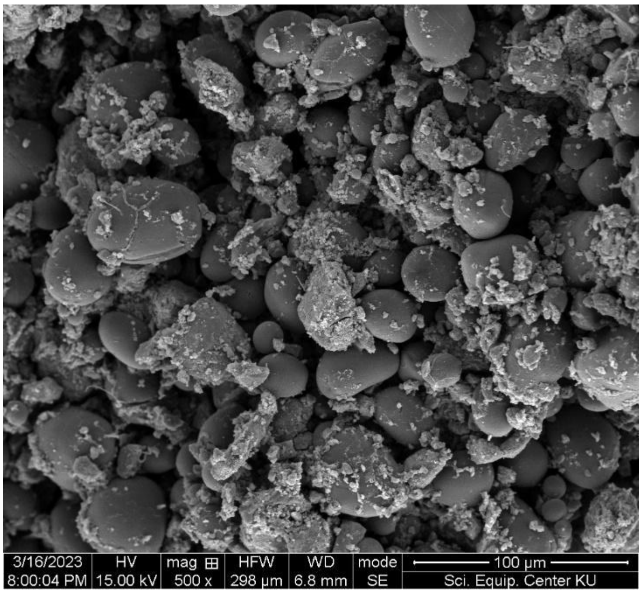
SEM images (Fig. 8) were analyzed using ImageJ (LOCI, University of Wisconsin, USA) software to quantify void size and distribution within the samples. This analysis provides a detailed assessment of void distribution, offering valuable insights into the sample's internal structure. In Fig. 9, the red areas in the left images represent pores within the sample, while the right images illustrate the outlined pore structures.

For the porosity analysis, Fig. 9a clearly demonstrates that pores are distributed throughout the interface between starch granules and the lunar simulant (TLS-01). This incompatibility between components results in reduced durability and mechanical strength. In contrast, Fig. 9b exhibits larger and more numerous pores compared to Fig. 9a. Finally, Fig. 9c shows a significantly lower number of pores than Fig. 9b, although the average pore size is slightly larger than in Fig. 9a.

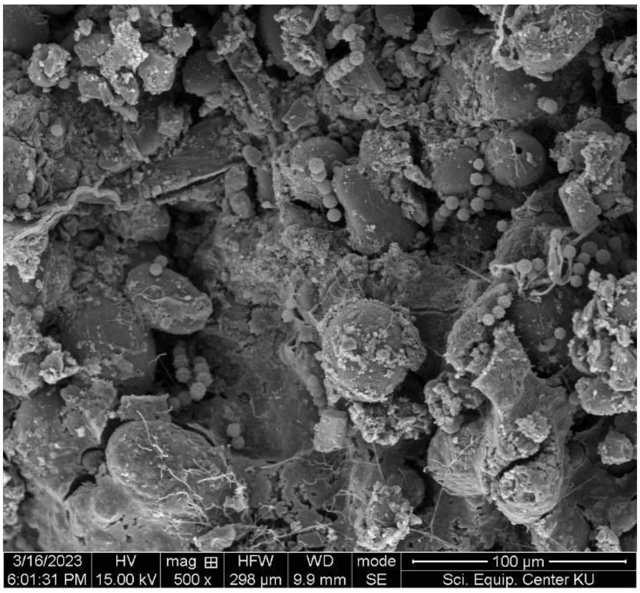
According to Table 4, LC-FeF-3W had the largest pore size, measuring 80.707 μm², while LC-1 had an average of 42.866 μm². Consequently, of the samples that showed the most compact and dense structure, LC-FrF-3 had the lowest porosity (5.349%), with an average pore size of 45.332 μm².



(a)



(b)



(c)

Fig. 8. SEM images of lunar mortar samples: (a) LC-1 sample has internal structural voids due to size mismatch between potato starch and TLS-01 particles, (b) LC-FeF-3W sample has poor cohesion and widespread voids due to expansion and cracking of potato starch upon heat treatment, and (c) LC-FrF-3 sample has dense cohesion and reduced voids, resulting in higher compressive strength.

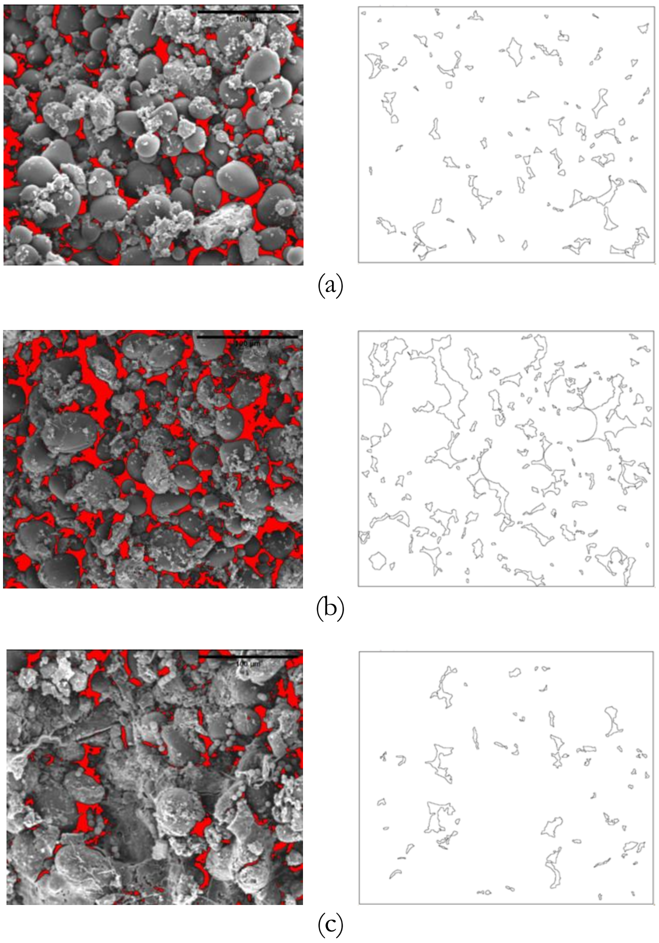


Fig. 9. Pore structure analysis of SEM image using ImageJ: (a) LC-1, (b) LC-FeF-3W and (c) LC-FrF-3.

Table 4 Pore size analysis results from SEM images using imageJ.

Sample	Area (%)	Average size (μm²)
LC-1	7.253	42.866
LC-FeF-3W	14.634	80.707
LC-FrF-3	5.349	45.332

3.3. Principal Component Analysis (PCA)

In order to reduce the dimensionality of the data and investigate the fundamental correlations and interactions between the variables, PCA was carried on the standardized dataset. Figure 10 shows the eigenvalues for each principal component as a bar chart. This bar chart shows a significant elbow following the third principal component, indicating that the first three components account for a significant portion of the overall data variability. This result is further verified by the cumulative explained variance ratio, which demonstrates that PC1 (48.47%), PC2 (27.23%), and PC3 (16.13%) collectively explain 91.87% of the overall variation. Therefore, the first principal component (PC1) describes the most variance (48.47%) in the data and has the highest correlation with the STR (compressive strength) values of lunar mortar.

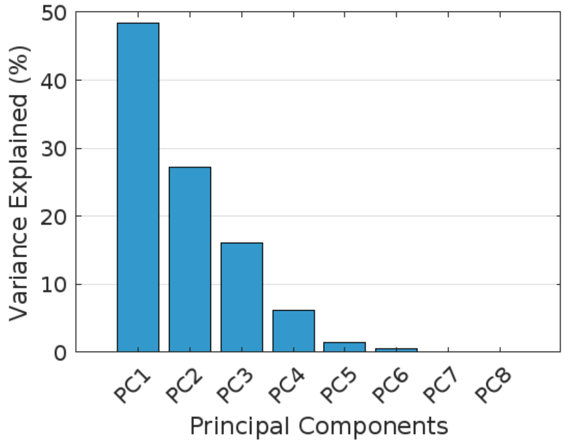


Fig. 10. The variance explained (%) by each principal component.

To further interpret these components, Fig. 11 shows a heat map of the contribution of the variables (lunar mortar ingredients) to the PCA factors (principal components), indicating the contribution or weight of each original variable to the respective principal component. For PC1, accounting for 48.47% of the variance, there were high positive loadings for the variables 'Heat' (0.510), 'Freeze' (0.486), and 'Potato starch' (0.4114) and high negative loadings for 'TLS-01' (-0.486). This implies that PC1 primarily depicts the variability related to the heat and freeze conditions, lunar simulant content, and potato fiber type. In PC2, accounting for 27.23% of the variance, the variables 'Potato fiber' (0.6633) and 'Potato fiber type' (0.6559) presented positive loadings, indicating that this component is significantly influenced by the amount of potato fiber and fiber type.

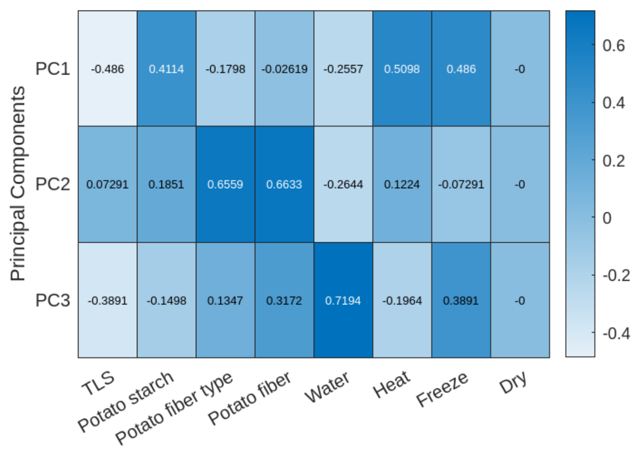


Fig. 11. Haet map of principal component loadings for lunar mortar ingredients.

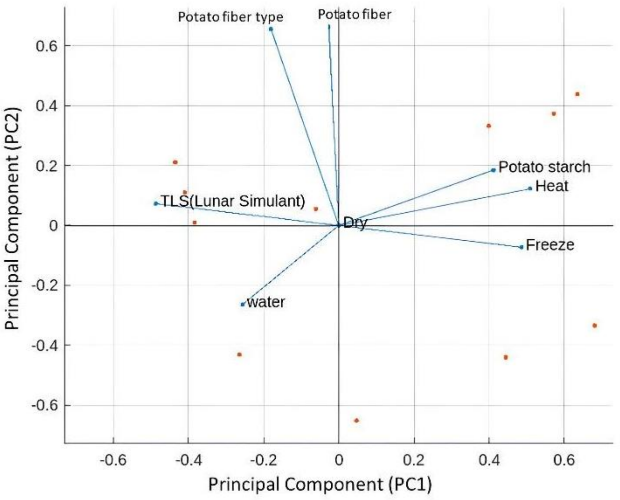


Fig. 12. Biplot of principal component loadings for variables influencing the development of lunar mortar from TLS-01 (lunar simulants).

The biplot (Fig. 12) shows that the angles between the variable vectors represent the correlations between the original variables. The biplot suggests that the variables "Potato Fiber Type" and "Potato Fiber" are positively correlated because their vectors are pointing in almost the same direction. This implies that these variables are related to each other's properties or characteristics of the lunar mortar mixture. In contrast, "TLS-01 (Lunar Simulant)" and "Potato starch" are negatively correlated because their vectors are pointing in opposite directions, suggesting that they have contrasting effects on the strength properties of mortar as represented by principal component 1. Similarly, the opposing directions of "Potato Fiber Type" and "Water" suggest that they have contrasting effects on the mortar compressive strength properties represented by principal component 2.

From the PCA, these variables "TLS-01 (Lunar Simulant)", "Potato starch", "Heat", and "Freeze" are those most likely to affect the values of compressive strength of the lunar mortar based on their large absolute loadings in PC1, which was the principal component most highly related to the values of STR.

3.4. Factors Influencing Lunar Mortar

The following key factors significantly influenced the compressive strength mechanical properties of the lunar mortar derived from lunar simulants:

1. **Lunar Regolith Simulant (TLS-01) Content:** The quantity and size of TLS-01 aggregates impact the strength of mortar. Increasing the proportion of TLS-01 aggregates from 38.09% to 48% resulted in an upward trend in the strength of the mortar. For example, the LC-1W mixture with a TLS-01 aggregate proportion of 38.09% exhibited a compressive strength of 0.02 MPa, whereas the LC-2 mixture with a TLS-01 aggregate proportion of 48% showed a compressive strength of 0.13 MPa.
2. **Potato Starch Content:** The quantity of potato starch affects the cohesion of mortar. SEM images reveal that the TLS-01 aggregates exhibit a small rectangular shape compared to the large spherical shape of potato starch. To minimize internal cracking within the structure, the amount of potato starch was reduced in the experiments conducted during stage III.
3. **Potato Fiber Type and Content:** The quantity and type of potato fiber affect the reinforcement and strength of mortar. During the experiments conducted in stage III, fresh potato fibers and fermented fibers were added at proportions of 3%, 5.6%, and 7.9%. Increasing the quantity of potato fiber resulted in an increasing trend of mortar strength. In comparison to fermented fibers, fresh fibers provide higher compressive strength values. For instance, the compressive strength values of the LC-FrF-3 formula were higher than those of the LC-FeF-3 formula. This difference may be attributed to the retting process, which caused the fibers to separate, unlike the fresh fibers that remained bonded together as a cohesive mat, resulting in higher strength.
4. **Water Content:** Water content affects the formability of mortar. During the first test phase, where the water content was 46.67%, some samples were unable to form properly. The water content was reduced to 17.86% and 33.34% in the second test phase. The suitable amount was determined to be 33.34% due to the unsatisfactory results obtained with a water content of 17.86%. The inconsistent mixture prevented homogeneous combination of the components. Therefore, in the third test phase, the water content started at 28%, and additional water was added based on the quantity of fibers incorporated in the subsequent formulas.
5. **Temperature Treatment**: Temperature impacts the structure and shaping of mortar. When the samples were subjected to freezing at -10 °C, they could be molded but could not maintain their shape. Therefore, wet wipes were used to wrap the samples in a cube shape and allowed to dry at room temperature. When heat was applied to the samples to increase strength, they expanded and resulted in a weakened structure. Hence, the temperature for shaping mortar is -10 °C, whereas the temperature for maintaining the shape is room temperature.

4. Conclusion

The development of lunar mortar compositions derived from Thailand Lunar Regolith Simulant (TLS-01) and potato-based materials, such as potato starch and fibers, has been extensively investigated in this research. The systematic experimental method used in this study examines how various factors affect the lunar mortar's compressive strength and microstructural characteristics.

The results indicated that the mortar samples tested after being cured for 5 days in Step III showed the best compressive strength (0.65 MPa). This was for the mortar mixture that had 39.47% TLS-01, 7.9% potato fibers, and had been frozen at -10 °C for 3 h. Microstructural analysis with SEM revealed that the LC-FrF-3 sample exhibited better compressive strength than other formulations due to its dense cohesion and fewer voids. Among all the tested samples, LC-FrF-3 had the lowest number of pores, which represents a more compact structure, while its average pore size was 45.332 μm^2.This was attributed to the uniform size of the fibers used for reinforcement, the absence of internal cracking from excessive heat, and the stable compressive strength values during testing.

PCA was used to identify the critical factors affecting the compressive strength of the lunar mortar. The study found that the factors "TLS-01 (Lunar Simulant)", "Potato starch", "Heat", and "Freeze" have the strongest relationships with the compressive strength values, as evidenced by their high loadings in the first principal component (PC1).

As a result, this study demonstrated that agricultural waste, such as potato-based materials, could be used with lunar simulants to produce lunar construction materials. The development of lunar mortar mixtures using local materials, such as lunar regolith simulants and potato-based materials, shows significant potential for making lunar construction sustainable and affordable. Notably, a lunar habitat must withstand an internal pressure of 34.5 kPa (~0.035 MPa) to support human life and endure stresses of at least 0.1 MPa. Although the compressive strength of 0.65 MPa is close to these requirements [23], it may be inadequate for primary structural support but could be well-suited for secondary structural applications such as thick radiation-shielding walls. While potato starch and fibers offer an innovative and sustainable approach to material use in construction, their application under lunar conditions faces substantial challenges. Durability issues related to radiation, temperature extremes, and the potential brittleness of organic materials must be addressed through further research and technological advances. If successfully adapted, these materials could provide a renewable and resource-efficient solution for future lunar habitats or structures to long-term viability on the Moon. Further research and refinement of these formulas could lead to the creation of durable and practical construction materials for future lunar missions and habitation.

Acknowledgment

This research is funded by Kasetsart University through the Graduate School Fellowship Program and was funded by the Undergraduate Research and Mentoring Fund (URMF) of the Faculty of Science, Kasetsart University. We especially thank Dr. Kanokorn Hanchanachum for her invaluable assistance in the use of laboratory facilities and equipment. Furthermore, we would like to sincerely thank Mr. Anurak Khamdaeng for giving potato fibers and Kanjana Concrete Company (Limited), Thailand and Space Zab Company, Thailand for kindly offering TLS-01.

This research project is partially supported by Chulabhorn Royal Academy (Fundamental Fund by National Science Research and Innovation Fund (NSRF): fiscal year 2024) (FRB670024/0240 Project code 198471).

Authors Declaration

During the preparation of this article, the authors used generative AI to refine sentence structures, grammar, and overall language quality. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

[1] M. Z. Naser and Q. Chen, "Extraterrestrial construction in lunar and martian environments," in *Earth and Space 2021*, Virtual Conference: American Society of Civil Engineers, Apr. 2021, pp. 1200–1207. doi: 10.1061/9780784483374.111.

[2] Z. Pei *et al.*, "Overview of lunar exploration and International Lunar Research Station," *Chin. Sci. Bull.*, vol. 65, no. 24, pp. 2577–2586, Aug. 2020, doi: 10.1360/TB-2020-0582.

[3] R. P. Mueller, "Lunar base construction planning," in *Earth and Space 2022*, Denver, Colorado: American Society of Civil Engineers, Jan. 2023, pp. 858–870. doi: 10.1061/9780784484470.072.

[4] J. J. Sokołowska, P. Woyciechowski, and M. Kalinowski, "Rheological properties of lunar mortars," *Applied Sciences*, vol. 11, no. 15, p. 6961, Jul. 2021, doi: 10.3390/app11156961.

[5] A. Akhnoukh, H. Al-Khateib, J. Edmunson, M. Fiske, and J. Fikes, "Developing concrete mixes using micro sized Lunar and Martian regolith for space applications," presented at *The ASC 2021. 57th Annual Associated Schools of Construction International Conference*, pp. 182–172. doi: 10.29007/4tl3.

[6] C. Dreier, "An improved cost analysis of the Apollo Program," *Space Policy*, vol. 60, p. 101476, May 2022, doi: 10.1016/j.spacepol.2022.101476.

[7] [7] H. Karaky *et al.*, "Characterization of beet-pulp fiber reinforced potato starch biopolymer composites for building applications," *Construction and Building Materials*, vol. 203, pp. 711–721, Apr. 2019, doi: 10.1016/j.conbuildmat.2019.01.127.

[8] A. D. Roberts *et al.*, "Blood, sweat, and tears: Extraterrestrial regolith biocomposites with in vivo binders," *Materials Today Bio*, vol. 12, p. 100136, Sep. 2021, doi: 10.1016/j.mtbio.2021.100136.

[9] Y. Sakai, "Production of hardened body by direct bonding of sand particles," May 04, 2021. doi: 10.20944/preprints202105.0017.v1.

[10] A.-L. Paul, S. M. Elardo, and R. Ferl, "Plants grown in Apollo lunar regolith present stress-associated transcriptomes that inform prospects for lunar exploration," *Commun Biol*, vol. 5, no. 1, p. 382, May 2022, doi: 10.1038/s42003-022-03334-8.

[11] N. Labeaga-Martínez, M. Sanjurjo-Rivo, J. Díaz-Álvarez, and J. Martínez-Frías, "Additive manufacturing for a Moon village," *Procedia Manufacturing*, vol. 13, pp. 794–801, 2017, doi: 10.1016/j.promfg.2017.09.186.

[12] S. Ma *et al.*, "3D-printed Lunar regolith simulant-based geopolymer composites with bio-inspired sandwich architectures," *Journal of Advanced Ceramics*, vol. 12, no. 3, pp. 510–525, Mar. 2023, doi: 10.26599/JAC.2023.9220700.

[13] L. Windisch *et al.*, "Geotechnical and shear behavior of novel lunar regolith simulants TUBS-M, TUBS-T, and TUBS-I," *Materials*, vol. 15, no. 23, p. 8561, Dec. 2022, doi: 10.3390/ma15238561.

[14] C. Xiao, K. Zheng, S. Chen, N. Li, X. Shang, F. Wang, et al., "Additive manufacturing of high solid content lunar regolith simulant paste based on vat photopolymerization and the effect of water addition on paste retention properties," *Additive Manufacturing*, vol. 71, p. 103607, 2023.

[15] R. Paradiso, A. Caporale, G. Liuzzi, M. Palladino, S. D. Pascale, and P. Adamo, "Mars regolith simulant as substrate for cultivation of higher plants in Space colonies: The need for organic amendment for potato as a case study," Copernicus Meetings, EGU23-14954, Feb. 2023. doi: 10.5194/egusphere-egu23-14954.

[16] T. Jirasirichot *et al.*, "Improving the quality of lunar regolith simulant soil for future food security," *Curr. Appl. Sci. Technol.*, vol. 23, no. 6, Apr. 2023, doi: 10.55003/cast.2023.06.23.008.

[17] S. Seehanam, S. Santironnarong, W. Meesuay, S. Soralump, W. Thowiwat, S. Jitklongsub, and W. Chancharoen, "Development and mechanical properties of the first Thailand lunar simulant (TLS-01)," in *Proceedings of the 2nd Innovation Aviation & Aerospace Industry-International Conference*, 2021, vol. 28, p. 30.

[18] *Industrial Product Standards Load-Bearing Concrete Block*, TIS 57-2533, Thai Industrial Standards Institute (TISI), Bangkok, Thailand, 2020

[19] H. Abdi and L. J. Williams, "Principal component analysis," *WIREs Comp Stat,* vol. 2, pp. 433–459, 2010, doi: 10.1002/wics.101.

[20] K. Pearson, "LIII. On lines and planes of closest fit to systems of points in space," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 2, no. 11, pp. 559–572, Nov. 1901, doi: 10.1080/14786440109462720.

[21] H. Hotelling, "Analysis of a complex of statistical variables into principal components," *Journal of Educational Psychology*, vol. 24, pp. 498–520, 1933, doi: 10.1037/H0071325.

[22] I. T. Jolliffe and J. Cadima, "Principal component analysis: A review and recent developments," *Phil. Trans. R. Soc. A.*, vol. 374, no. 2065, p. 20150202, Apr. 2016, doi: 10.1098/rsta.2015.0202

[23] *NASA Human Health, Medical, and Performance Spaceflight Standards*, NASA-STD-3001 Volume 2, National Aeronautics and Space Administration (NASA), Houston, Texas, 2023.

Sutatta Tayadhammadhat was born on July 1st 2000, in Bangkok, Thailand. She earned the bachelor's degree in Earth Science from Kasetsart University, Thailand, in 2023. She is currently a Master's degree student in the Department of Earth Science at Kasetsart University. Her research interests include Planetary Sciences and Materials Sciences.

Theingi Nwe was born on Janaury 13th, 1989, in Myitkyina, Kachin State, Myanmar. She earned a bachelor's degree in Mechanical Engineering from Technological University Myitkyina in 2009 and a master's degree in Mechanical Engineering from Yangon Technological University, Yangon, Myanmar, in 2018. In recognition of her academic achievements, she was awarded the prestigious KMITL Doctoral Scholarship to undertake her doctoral studies in Mechanical Engineering at the School of Engineering, King Mongkut's Institute of Technology Ladkrabang, where she successfully obtained her Ph.D. in March 2024. She is currently a lecturer in the Department of Mechanical Engineering at Naypyitaw State Polytechnic University, Myanmar, where she has been serving since 2010. Her research interests include railway transportation engineering, finite element modeling and analysis, fracture mechanics, failure analysis, biomechanics, and space engineering.

DOI:10.4186/ej.2025.29.2.81

Supan Yodyingyong, born on October 4th, 1982, in Maha Sarakham, Thailand, holds a B.Sc. in Chemistry from Maha Sarakham Rajabhat University and a Ph.D. in Science and Technology Education from Mahidol University. He is a faculty member at Mahidol University's Institute for Innovative Learning, specializing in silica aerogel synthesis, nanostructured materials, and chemical education. With over 13 years of research experience, Dr. Supan holds multiple international patents in aerogel synthesis.

Wares Chancharoen was born on November 18th, 1989, in Bangkok, Thailand. He received the B.S. degree in mechanical engineering from King Mongkut's University of Technology Thonburi, Thailand, in 2012 and the M.S. and Ph.D. degrees in information science at Nagoya University, Japan. He is currently a lecturer at Princess Srisavangavadhana Faculty of Medicine, Chulabhorn Royal Academy, Thailand. His research interests include space medicine, space engineering, mechanical engineering, and medical device design. In 2018, he was awarded the Emerging Space Leadership (ESL) from the International Astronautical Federation (IAF), France. In 2019, he received the recognition award from the Deep Space Food Challenge as one of the international teams around the world from phase 1, which was conducted by The National Aeronautics and Space Administration (NASA), the Canadian Space Agency (CSA) and the Methuselah foundation.

Sarinya Paisarnsombat was born on January 16th, 1986, in Prachuap Khiri Khan, Thailand. She received her B.S. (Second Class Honours) in Chemistry from Kasetsart University, Thailand in 2008 and Ph.D. in Geology from University of New Brunswick, Canada in 2016. During her study, she was fully funded by the Royal Thai Government under the Development and Promotion of Science and Technology Talents Project (DPST). She is currently a lecturer at Department of Earth Sciences, Faculty of Science, Kasetsart University, Thailand. Her research interests include a board area of Planetary Sciences such as meteorite, tektite, impact process, and materials for space science. Her research also focuses on application of geology and earth materials in space science and technology.