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Research Article

Traditional flat earthen roofs of Kemaliye, Erzincan: material characterization and implications for sustainable earth architecture

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ABSTRACT

The flat earthen roofs of Kemaliye houses represent a rare and well-preserved example of traditional earthen roofing systems in Anatolia. However, their material composition and performance mechanisms remain insufficiently documented in scientific literature. The main objective of this study is to characterize the earthen and stone materials used in the original flat roofs of Kemaliye houses and to evaluate their physical, geotechnical, and water-related performance in relation to roof functionality. For this purpose, original roof materials were collected in situ and analyzed using geotechnical index tests, mineralogical and chemical analyses as well as physical and mechanical tests conducted on mortar specimens prepared with different water contents. The results indicate that the upper roof soil (gavcin) exhibits low plasticity and a mineralogical composition dominated by quartz and calcite, which provides adequate workability while limiting excessive swelling behavior. Mechanical testing reveals compressive strength values in the range of approximately 2.7–3.7 N/mm² and a non-linear relationship between water content, porosity, and strength. Capillary absorption tests demonstrate that the material-level sensitivity to water is effectively mitigated in practice by the layered roof configuration and traditional construction details. These findings indicate that the long-term durability of Kemaliye flat roofs depends not solely on the use of water-resistant materials, but rather on the integrated interaction between material properties, compaction, and roof detailing. The study provides a scientific basis for the conservation of this heritage roofing system and offers transferable insights for the development of durable and sustainable earthen roof solutions in contemporary architecture.

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INTRODUCTION

Traditional Kemaliye houses are in the Anatolian region and have persisted since the late 19th century as examples of cultural and architectural heritage with their unique construction techniques (Fig. 1a,b). One of the most significant characteristic features of traditional Kemaliye houses is the flat earthen roof covering, known as “rıhtım,” which is lined

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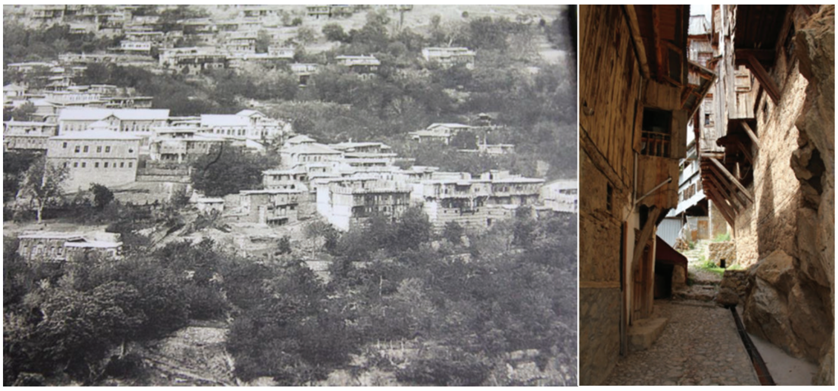
with river stones. The research on the construction technique of these flat earthen roofs was conducted by comparing data obtained during field studies with interviews held with local craftsmen [1].

The comprehensive research revealed that the use of "Rıhtım" stones in the original flat earthen roofs of Kemaliye houses is unique to the region and its surrounding villages, with no similar application found elsewhere in Anatolia or the Mediterranean region. The completed for the roof is shown in Figure 2a and the log stone which is the rolling stone for the purpose of compaction is shown in Figure 2b.

Another unique feature of the flat earthen roofs of Kemaliye houses is the presence of a secondary drainage system, in addition to the gutter system developed to drain rainwater. In this secondary drainage system, an inclined wooden element called "fitil" runs around the entire roof. It is thought that this "fitil" element not only helps prevent leaks through joint gaps but also functions as a capillary barrier to ensure water drainage (Figure 3).

Once the ceiling planks are fixed in place, the exposed beam ends along the sides are covered with a fascia board to give a clean and protective edge. On top of this fascia, a sloped wooden piece called the "fitil" is installed, helping guide excess water toward the main drainage channel, known as the "corten."

After this, a second fascia board is added to form a shallow basin that will hold the subsequent soil layers. Wooden members called "mertek" or "kaplama tahtası" are then laid across the planks to create the base support for the roof build-up. The first soil layer, known as "yaskuru," is then spread evenly and left to dry. This layer plays an important role in thermal insulation, and its porous structure helps regulate moisture and temperature within the earthen roof system. Next, a layer of finely sifted clayey soil called "gavcin" is spread and moistened using a dipper stone known as "Rıhtım" are then hammered into place to create a flat surface. After all gaps are filled, the roof is



(a) (b)

Figure 1. a) Original flat-roofed houses in the center of Kemaliye (Kemaliye Municipality archive, undated photograph); b) Yakupaga Mansion.

(a) (b)

Figure 2. a) Rıhtım stone on the flat earthen roof of a Kemaliye house, Kemaliye, 2019; b) Log stone, Kemaliye, 2019.

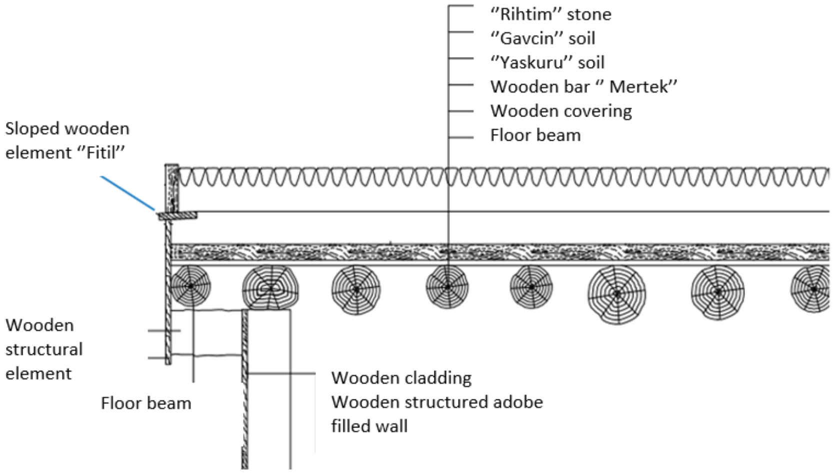


Figure 3. Cross-section of the original flat earthen roof of Kemaliye houses [2] [created by author].

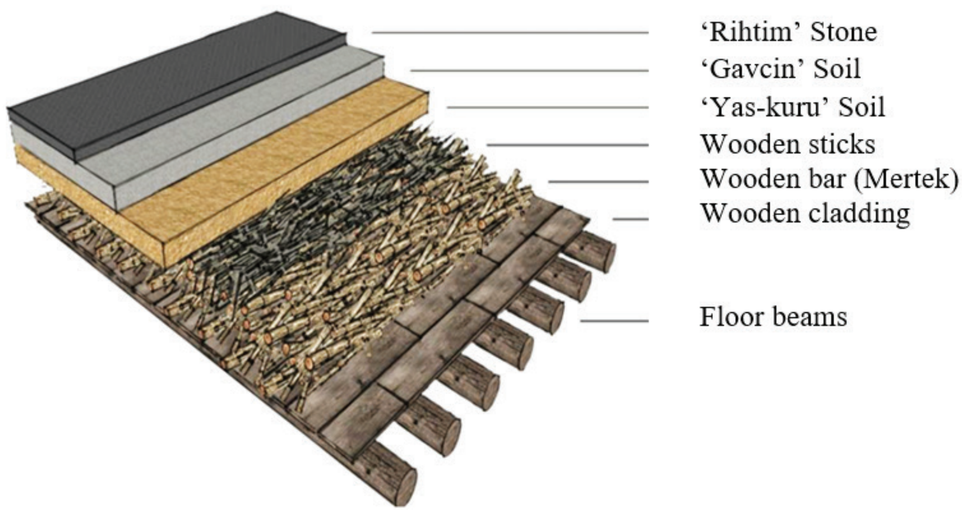


Figure 4. Layers of flat earthen roofs of Kemaliye houses.

compressed and leveled using a heavy stone called a "log tasi". This ensures complete compaction of the soil.

MATERIAL AND METHODS

Materials

The primary objective of this study is to characterize the earthen and stone materials used in the original flat roofs of Kemaliye houses and to assess their physical, geotechnical, and hydraulic performance with respect to roof functionality. The materials used in the original roofs, including "yaskuru" soil, "gavcin" soil, and "Rıhtım" stone, were obtained from the Kemaliye area and the material properties were determined in the laboratory. Gavcin soil was used in this study because of its critical role as the water-shedding layer in traditional flat earthen roofs. This material is locally abundant and has been historically used due to its favorable plasticity and water retention properties, which allow it to form a dense, cohesive, and low-permeability surface when compacted. It's flexible with minor movements and flexing without cracking. It can keep water out even in the elements, so it's perfect for this build. Therefore, experiments are deliberately carried out on the Gavcin soil because it is the main material that makes the roof system waterproof and durable in the long term. Rıhtım stone, on the other hand, is another locally available, cost-effective, and sustainable material traditionally preferred by local communities. It is commonly used as a supporting and protective layer in traditional construction systems, providing mechanical stability and durability while complementing the water-shedding function of the Gavcin soil.

EXPERIMENTAL STUDY STEPS
Obtaining Original Materials and Determining Inner Structure and Geotechnical Properties • XRF Analysis • XRD Analysis • Petrographic Analysis • Granulometry and Hydrometer Analysis [3] • Bulk Unit Weight of Grains [3] • Consistency Limits [3]
Production of Mortar with Different Water Contents and Determination of Physical and Mechanical Properties of The Produced Mortars • Sample production [4] and local craftsman Mustafa Malkoç) • Fresh state consistency and bulk unit weight [5, 6] • Bulk density and specific gravity [7, 8] • Compactness - porosity and water absorption by weight - volume • Capillary water absorption [9, 10] • Solubility in water [11] • Compressive strength [12] • Flexural - tensile strength [12]

Figure 5. Experimental study steps.

The experimental study was designed in two phases; in the first phase, the inner structure and geotechnical properties of the original materials brought from Kemaliye were determined, while in the second phase, mortar samples were produced using "gavcin" soil with different water contents, and the physical and mechanical material properties of these samples were examined (Fig. 5)

DETERMINATION OF THE INNER STRUCTURE AND GEOTECHNICAL PROPERTIES OF THE MATERIALS

In the first phase of the experimental study, the soil and stone materials used in the original flat earthen roofs were obtained from Kemaliye, Erzincan. The inner structure properties of the soil and stone materials obtained from the field were studied at Istanbul University-Cerrahpaşa Faculty of Engineering, while their geotechnical properties were determined in the geotechnical laboratory of the Civil Engineering Faculty at Yıldız Technical University. In the study, a single type of "gavcin" soil was used, while two types of soil obtained from the field were used for "yas-kuru". The codes of the original materials used in the experiments are provided in Table 1.

Table 1. Given codes of original materials

Code	Explanation
R	"Rıhtım" Stone
Y1	"Yas-kuru" Soil (Type 1)
Y2	"Yas-kuru" Soil (Type 2)
G	"Gavcin" Soil

Obtaining Original Materials

In the traditional earthen roofs of Kemaliye houses, only a type of clay soil known as "gavcin" (cohesive soil) is used as the top layer, and limestone gravel called "Rıhtım" is placed on top (Fig. 6a-c). However, the lower layer, referred to as "yas-kuru" soil, can be selected from various soil types with different properties. During the field and laboratory studies conducted by the Faculty of Architecture at Yıldız Technical University within the scope of TUBITAK (The Scientific and Technological Research Council of Turkiye) project number 217M561, different types of cohesive and non-cohesive soils were observed as "yas-kuru" soil.

Gavcin soil is generally obtained from specific locations (such as the cave front in Sandikbagi Neighborhood, Toybelen Village, and Kiligin Cave in Sirakonak Village) and does not show significant variability as a soil type. The gavcin soil used in the study was obtained from the tunnel construction along the road to Yaka Village, located across from the Prof. Dr. Ali Demirsoy Doga Tarihi Muzesi (Natural History Museum), as shown in Figure 7.

Structural properties of the specimens

In order to determine the structural characteristics of the materials obtained from the field, research was conducted at the Faculty of Engineering, Istanbul University-Cerrahpaşa. The internal structural properties were examined, and chemical, mineralogical (using XRF and XRD), and petrographic analyses were performed on

(a) (b) (c)

Figure 6. Materials used during the research a) “Gavcin” soil, b) “Yas-kuru” soil, c) “Rıhtım” stone.

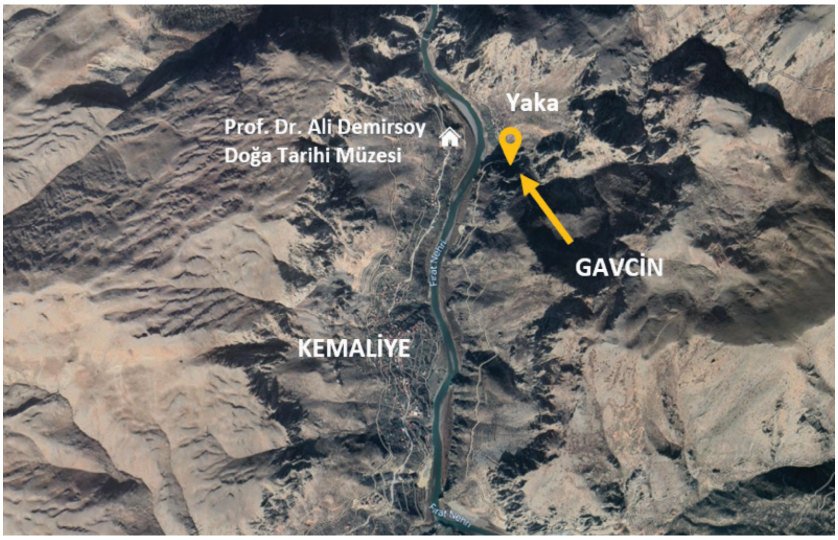


Figure 7. Location of the site where the gavcin soil used in the study was extracted (39° 15´ N, 38° 29´ E).

samples of gavcin, yaşkuru, and Rıhtım stone. The XRD patterns of the samples labeled Rıhtım (R), Gavcin (G), and Yaşkuru-1 (Y-1) are provided in Figures 8, 9, and 10 respectively.

The most intense peak is labeled with calcite located around 27-28 degrees (2θ), suggesting that calcium carbonate is the predominant phase in the sample. The peaks labeled “Quartz” confirm that crystalline quartz is present in the sample, while the most dominant diffraction responses belong to calcite, which is the crystalline form of calcium carbonate ($CaCO_3$). The strongest peak observed at around 27–28° (2θ) clearly shows that calcite is the main mineral phase in the R stone. This is fully consistent with its limestone origin and helps explain why the material behaves in a relatively stiff and well-cemented manner. When there is a lot of calcite in the mix it is normally stronger and less plastic. This is mainly because the crystals lock together tightly. But quartz does not do much chemically, it makes the material physically tough, increasing hardness and wear resistance. They make a perfect natural team, with the calcite gluing everything together and the quartz providing the hard, load-bearing backbone.

Figure 9 shows the XRD pattern of the Gavcin (G) specimen in which the peaks are in accordance with the different crystalline phases in the material. The minerals identified are clinochlore, illite, cristobalite, quartz, calcite and manganoan phases. The maximum peaks indicate that the minerals are the most abundant and the multiple reflections at various 2θ angles support the idea that the soil is a mixture of various minerals and not just one dominant phase with quartz and illite being the most prevalent. The soil of Gavcin is rich in non-expansive to slightly expansive clay minerals, illite that strongly controls the plasticity and shear strength of the soil. Its presence indicates that the soil

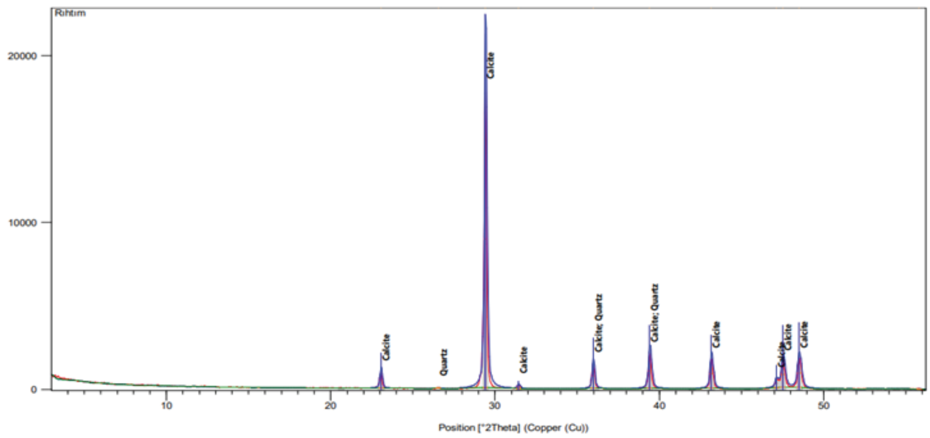


Figure 8. The XRD pattern of rıhtım (R) stone.

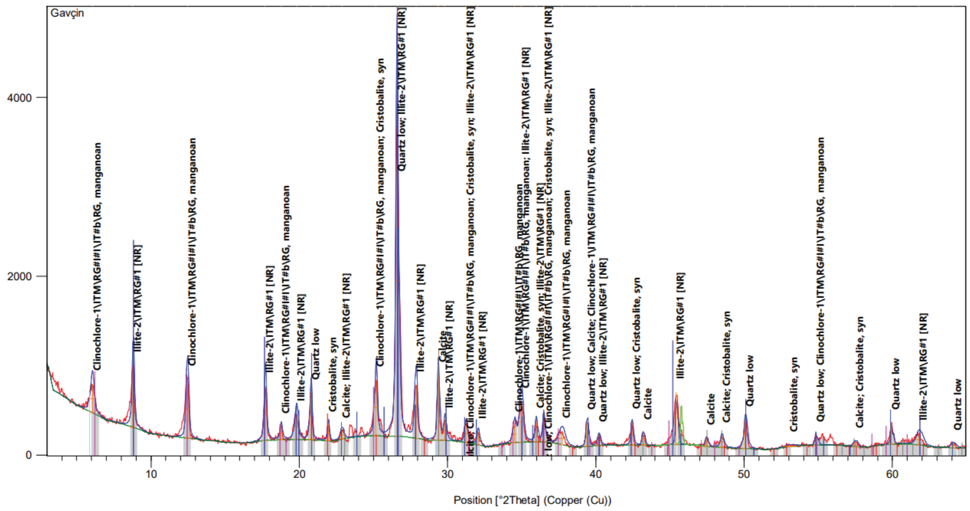


Figure 9. The XRD pattern of gavcin (G) specimen.

is of moderate plasticity and somewhat sensitive to changes in moisture content, but considerably less so than highly expansive clays such as smectite. Clinochlore, a member of the chlorite group, contributes to the fine-grained texture of the soil and maintains a low swelling potential, while introducing some directional mechanical behavior. The high peaks of quartz indicate a high percentage of rigid non-clay particles in the soil matrix, which increases the frictional resistance and decrease the compressibility. Cristobalite, a silica polymorph, suggests silica-rich formation processes and can result in a more brittle soil structure. The calcite meanwhile suggests the partial carbonate bonding, or weak cementation effects, that locally increase the stiffness and strength. Finally, the minor manganoan phases point to trace geochemical components that might affect color and localized bonding but won't really impact the overall mechanical behavior.

The XRD pattern of Y-1 shows a mix of clay minerals and other components (Fig. 10). This is why it was so difficult to find the limits of its consistency and demonstrate how unpredictable this soil can be with moisture changes. This is because there are several different clay minerals involved, and these have different interlayer spacings and surface charges. This variation greatly influences the absorption of water by the soil and the interaction of the particles between them. This mineralogical complexity also explains why it was difficult to define limits of consistency, since each clay mineral behaves differently with changes in moisture content. Furthermore, non-clay minerals such as quartz and carbonate phases provide stiffer particles in the soil matrix that impair the uniform deformation and thus the response is more irregular and non-linear at different water contents. Consequently, the Y-1 specimen is expected to exhibit complex mechanical and hydraulic behavior,

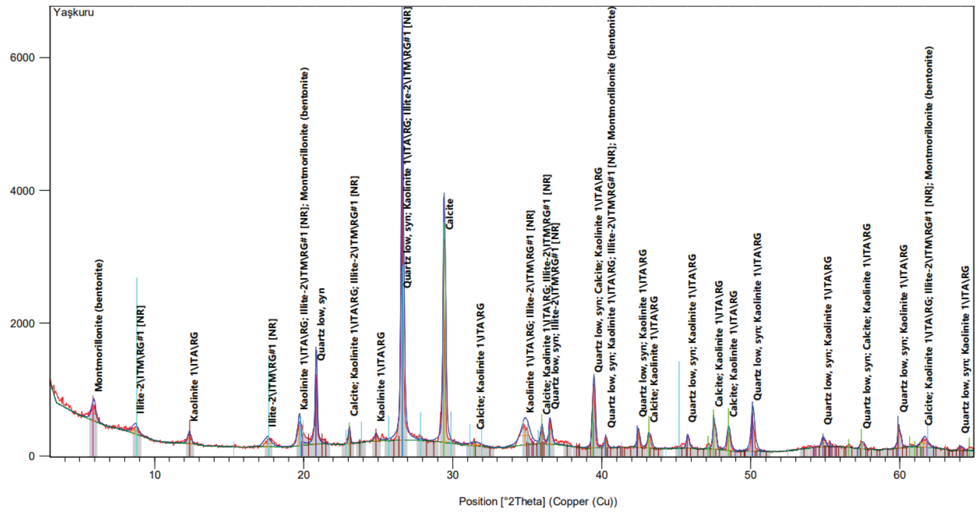


Figure 10. The XRD pattern of yaskuru-1 (Y1) specimen.

Table 2. Relative mineral abundances in the specimens

Specimen	Relative mineral abundances
Gavcin (G)	Kalsit, ilit, klorit, kuvars
Yaskuru-1 (Y-1)	Montmorillonit, kalsit, ilit, kaolinit, kuvars
Rıhtım (R)	Kalsit, kuvars

particularly under cyclic wetting–drying or loading conditions, which is consistent with the observed challenges in laboratory characterization.

The contents observed from the XRD patterns of the Gavcin, Yaskuru (Y-1), and Rıhtım (R) samples are summarized in Table 2. The chemical properties of the specimens were also summarised in Table 3.

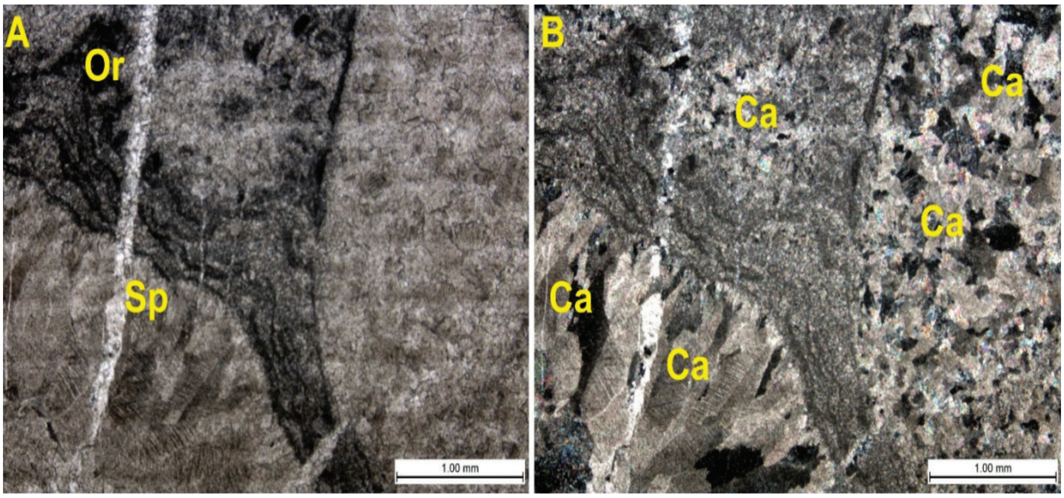
Table 3 shows the chemical contents of three different specimens (G, Y-1, and R) as determined by X-ray fluorescence (XRF) method which is a non-destructive analytical technique that uses high-energy X-rays to determine the elemental composition of materials. Silicon Dioxide (SiO_2) is the major component, indicating a high presence of silicate minerals as 48.34%. Also, a significant component, suggesting the presence of Aluminum Oxide (Al_2O_3) with 23.02% content. 9.59% indicates the number of volatile substances lost upon heating, such as water or carbonates. The Yaskuru (Y-1) specimen includes the same components with percentages of 45.6 % and 14.36%, respectively. The 12.33% of LOI, which is higher than in G, indicate more volatile components, possibly more organic material or carbonates. The predominant component, suggesting that Rıhtım stone (R) is primarily composed of calcium-bearing minerals, likely calcite or limestone. The LOI (Loss of ignition) ratio is extremely high, indicating a large amount of volatile material, which could be due to a significant number of carbonates or water content.

Table 3. The chemical contents of the specimens were revealed by XRF method

Element oxide	Specimens		
	G	Y-1	R
SiO_2	48.34	45.6	0.97
TiO_2	1.03	1.04	0.00
Al_2O_3	23.02	14.36	0.59
Fe_2O_3	2.09	6.77	0.08
MgO	2.55	2.19	0.34
MnO	0.04	0.08	0.00
CaO	7.02	13.53	54.23
Na_2O	0.98	0.14	0.00
K_2O	5.02	3.67	0.04
P_2O_5	0.15	0.12	0.04
SO_3	0.04	0.03	0.03
LOI*	9.59	12.33	43.64
SUM	99.87	99.86	99.96

*LOI: Loss on ignition

Petrographic textures of the Rıhtım (R) stone under a microscope, with two distinct images labeled as a and b, are shown in Figure 11. The images display different minerals, labeled as “Or,” “Sp,” and “Ca,” which correspond to Orthoclase, Sphene and Calcite. The orthoclase is shown in a darker region, indicating its presence in the stone. The sphene mineral appears adjacent to the orthoclase/orthopyroxene in the stone. The texture in Figure 11a suggests that these minerals are closely associated and may form a



(a) (b)

Figure 11. a, b. The petrographic texture of the rıhtım stone (R).

particular texture, such as intergrowth or simple adjacency, within the rock. The texture shows multiple regions where calcites are distributed within the stone. The distribution of calcite appears more widespread in Fig. 11b compared to the minerals shown in Figure 11a. This indicates a significant presence of calcite, likely filling fractures, forming veins, or constituting a major component of the rock. The presence of these minerals in the given textures could indicate a metamorphic origin with subsequent hydrothermal alteration, especially if calcite is found in veins or as a secondary mineral filling crack.

Determination of Geotechnical Properties

In this study, the geotechnical properties of Gavcin and two types of Yaskuru soil were determined. Firstly, the soil material was sieved through an 8 mm diameter sieve, as practiced in the original flat earthen roofs in Kemaliye. Then, in accordance with the TS 1900-1 standard, a granulometric and hydrometer analysis was performed to define the soil classifications. To determine the specific gravity of the particles of the original materials, a specific gravity test for fine-grained soils was conducted. The consistency limits—liquid limit, plastic limit, and plasticity index—were determined using the Casagrande apparatus, following the TS 1900-1 standard. The particle size distributions of the materials are shown in Figures 12–14, while the results of the dry sieve analysis are presented in Table 4. The specific gravity values of the particles and the consistency limits of the materials are shown in Table 5.

Figure 12 shows the grain size distribution for the Gavcin (G) specimen. The curve indicates a wide range of particle sizes, with the percentage decreasing uniformly with decreasing grain size. This proves the sample is mostly fine-grained, since a large part of it passes right through the finer sieves.

Table 4. Results of the sieving

Sieve size (mm)	Sieve Number	Y-1		Y-2		G	
		EG(g)	EG(%)	EG(g)	EG(%)	EG(g)	EG(%)
8.000		403.6	100.000	400.2	100.000	500	100.000
4.750	4	397	98.365	381.5	95.315	461.8	92.360
2.000	10	376.2	93.211	264.7	66.141	3662	73.240
0.850	20	307.8	76.264	154..8	38.701	281.8	56.360
0.425	40	171	42.369	91.82	22.944	224.2	44.840
0.250	60	75	18.583	62.61	15.645	191.8	38.360
0.150	100	73	18.087	46.95	11.732	175.8	35.160
0.075	200	36	8.920	28.95	7.234	156.2	31.240

EG (g): Amount of material passing
EG (%): Percentage of material passing

Table 5. Dry unit weight of the specimens and consistency limits

Specimen	Y-1	Y-2	G
Unit weight γ (kN/m³)	26.8	27	27.5
Liquid limit (Wl) %	-	29.6	26.6
Plastic limit (Wp) %	-	22.6	20.9
Plasticity index (Ip) %	-	7	5.7

- Could not be measured.

The last study of Gokyiğit et al. [11] made a geotechnical experimental investigation on Gavcin, by mixing it with NHL, CL, bentonite, starch, and fly ash. The Yaskuru grain size distribution is very much like Gavcin. It is a broad, continuous distribution of particle sizes. Both curves run along the same line with a constant decrease of the percentage of material passing as the grain size decreases. This shows that Yaskuru (Y-1) also has a relatively fine-grained structure, since most of the material passes right through the finer sieve sizes (Fig. 13).

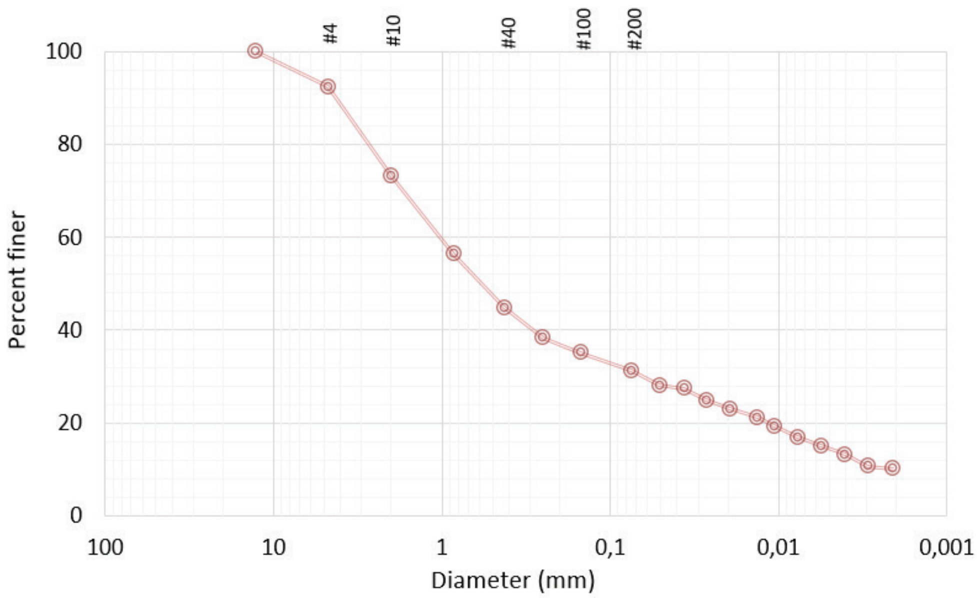


Figure 12. Grain size distribution of Gavcin (G) specimen.

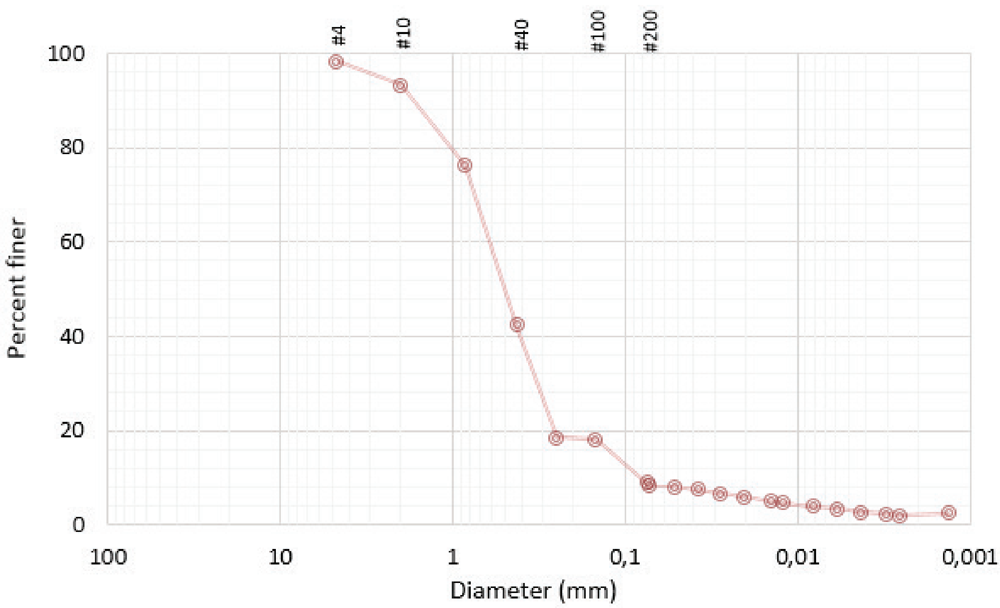


Figure 13. Grain size distribution of yaskuru (Y-1) specimen.

Figure 14 shows the grain size distribution for the Yaskuru sample (Y-2). As the grain size drops, the percentage of material passing through the sieves goes down too, which just means the sample doesn't have many fine particles. The distribution curve starts right near 100% at the largest sieve size (4.750 mm)—since almost all the material falls right through it—and then flattens out at the smaller sieve sizes, showing how little fine fractions are actually in the mix. Table 4 breaks down these sieve analysis results for all three samples (Y-1, Y-2, and G), tracking the sieve sizes (mm) and sieve numbers alongside the mass of material passing (EG, g) and the final percentage passing (EG%) for each sieve.

The unit weight (γ), liquid limit (Wl), plastic limit (Wp), and plasticity index (Ip) of the specimens labeled Y-1, Y-2, and G are given in Table 5. The dry unit weight of three specimens varies from 26.8 to 27.5 kN/m3 indicating that there is a slight variation in the density of the specimens. The water content at the liquid limit is where the soil transitions from a plastic to a liquid state, with specimen Y-2 having a higher liquid limit (29.6%) than specimen G (26.6%), and the liquid limit for Y-1 could not be determined. The plastic limit is the water content at which the soil changes from a semi solid to a plastic state. Specimen Y-2 has a plastic limit of 22.6 %, specimen G is slightly lower at 20.9 %, but the plastic limit for Y-1 could not be measured. Finally, the plasticity index (the difference between the liquid and plastic limits and indicates the moisture range in which the soil remains plastic) was calculated at 7 percent for Y-2 and 5.7 percent for G, but could not be calculated at all for Y-1.

DETERMINATION OF THE PHYSICAL AND MECHANICAL PROPERTIES OF MORTAR SAMPLES

To determine the short- and long-term physical and mechanical properties of the soil building materials used in the original flat earthen roofs of Kemaliye houses, and to investigate the relationship with water, mortar samples were produced using the original soil material and different water contents. The properties of these samples were examined, including the consistency in the fresh state, bulk unit weight in the fresh state, consistency determination using a vicat apparatus, specific weights and bulk densities in the hardened state, compactness-porosity characteristics, water absorption by weight and volume, capillary water absorption, solubility in water, and flexural-tensile strength as well as compressive strengths. In this study, due to the limitation of the water relationship in the roof cross-section to the upper soil layer, gavcin soil was used as the original material in the experimental study.

Production of Mortar Samples

To conduct physical and mechanical material tests, mortar was first produced using the original soil material (gavcin). Since there was no suitable standard to determine the amount of water to be used during production, the criteria outlined in EN 1015-2 [4] were considered. According to these criteria, it was determined that the bulk unit weight of the mortars produced should be greater than 1200 kg/m³ and that the target spread diameter should be 175±10 mm, as specified in EN 1015-6 and EN 1015-2 [4, 7]. Considering the required spread amount (175±10 mm) according to the

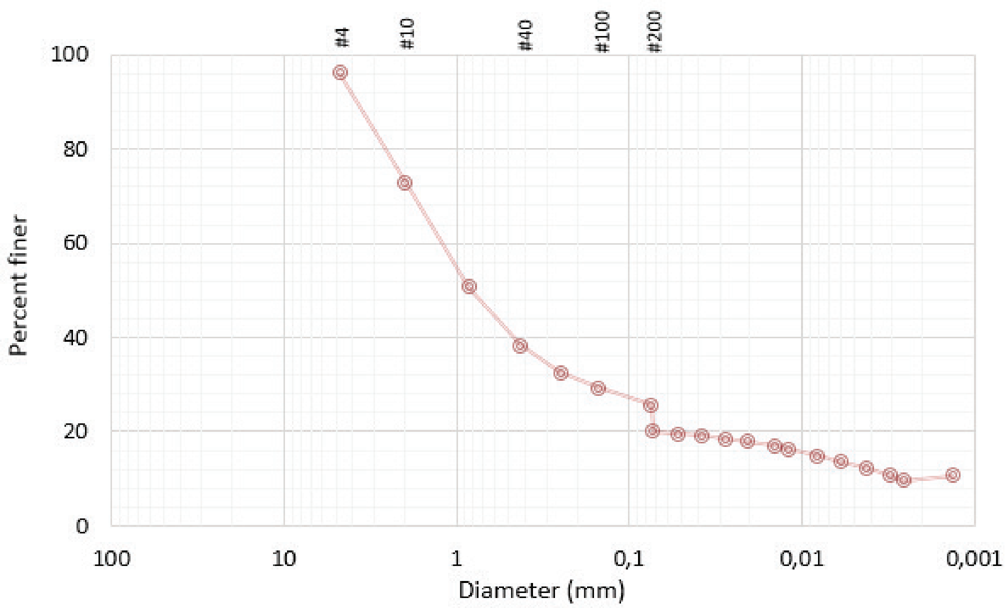


Figure 14. The grain size distribution of yaskuru (Y-2).

Table 6. Prepared specimens

Specimen	Description
G%29	Gavcin specimen prepared at 29% water content
G%29-l	Gavcin specimen prepared at 29% water content (Prepared for 365. Day tests)
G%22	Gavcin specimen prepared at 22% water content
G%17	Gavcin specimen prepared at 17% water content

EN 1015-2 [4] standard, the water content in the mortar produced with the original material was set at 29%.

In this study, in addition to the water content determined according to the EN 1015-2 standard [4], the appropriate water content for the soil to be spread, compacted, and for the limestone gravel to be placed on the roofs of Kemaliye Houses was also considered. In this context, suitable water contents for producing the roofs were determined in collaboration with local craftsman Mustafa Malkoç, who was born and raised in Kemaliye and works in the area. Original samples were also produced at water contents of 17% and 22%, as determined with the local craftsman. The samples were coded as shown in Table 6, considering their water contents.

According to the procedure followed during the mixing of the samples, the binder (gavcin soil) and water were mixed at low speed (62 r.p.m.) for 60 seconds, and then mixed at high speed (125 r.p.m.) for 30 seconds to produce the samples. The produced samples were placed in molds sized 40x40x160 mm, in two layers, with each layer being vibrated on a shaking table according to EN 1015-11[12] standards. Eventually, we prepared 54 original samples in total, with 29% water content (1.8), 22% water content (1.8) and 17% water content (1.8). In the testing phase, the fresh state consistency and bulk unit weight of the original material were measured according to EN 1015-3 and EN 1015-6 [5, 6]. Finally, the consistency characteristics of the material were determined by using the Vicat apparatus. The consistency values of the original samples at water contents of 17% and 22%, determined in collaboration with the local craftsman, were measured at 1 hour, 2 hours, 1 day, 2 days, 3 days, and 4 days. Accordingly, the consistency measurements of the original material are provided in Table 7, while the physical properties in the fresh state are shown in Table 8.

Table 7. Consistency measurements of mortar samples

Specimen	Consistency Measurement (mm)					
	Production time	1st hour	2nd hour	1st day	2nd day	3rd day
G1%22	9	15	20	30	38	40
G1%17	30	32	36	38	40	-

At the moment of consistency

Table 8. The physical and mechanical properties of the specimens

Specimen	G1% 29	G1%29-l	G1%22		G1%17	
Mean flow diameter (mm)	175	175	150		125	
Cavity unit weight (kg/m^3)	2114	2114	2150		2234	
Unit weight (g/cm^3)	1.8	1.9	1.9		2.0	
Specific gravity	2.7	2.5	2.6		2.6	
Compactness (%)	72	76	79		76	
Porosity (%)	28	24	21		24	
Volumetric water absorption (%)	4.84	2.63	5.54		6.12	
Water absorption by weight (%)	2.5	1.38	2.88		3.07	
Capillarity coefficient (kg/m$^2\sqrt{s}$)	0.46	0.57	0.29		0.30	
Capillary rise (cm)	1.5	2.5	1		1	
Water solution (hour)	1	1	1		1	
			28th day	**180th day**	**28th day**	**180th day**
Compressive strength (N/mm^2)	-	-	2.1	3.6	2.7	3.7
Bending strength (N/mm^2)	-	-	0.8	1.1	1	1.2

Table 8 outlines various physical and mechanical properties of different specimens labeled G1%29, G1%22, and G1%17. The table includes properties such as mean flow diameter, cavity unit weight, unit weight, specific gravity, compactness, porosity, volumetric water absorption, and others.

Additionally, compressive and bending strengths are provided for two different time intervals; 28 and 180 days. The 28-day age is the global standard for design and acceptance, as ordinary cement-based materials reach most of their ultimate strength by this time and the results are practical, reliable, and comparable across standards. The 180-day age is used to evaluate long-term behavior, especially for materials with slow reactions such as fly ash, slag, or stabilized soils, where pozzolanic and secondary reactions continue to improve strength and durability. The 365-day is used for the determination of the ultimate strength of a material. G1%29 had the widest spread with the highest mean flow diameter (175 mm) and a specific gravity of 2.7 showing that it was less dense and could not pack together as tight as the others resulting in higher porosity. On the flip side, G1%22 and G1%17 didn't spread as much—showing lower flow diameters of 150 mm and 125 mm—but their higher unit weights and specific gravities prove that these mixes formed a much denser, tighter structure. Over time, every single sample got stronger. Both compressive and bending strengths climbed between day 28 and day 180, clearly showing that the material was successfully curing and hardening over time. Sample G1%17 exhibits the highest compressive and bending strengths at 180 days, indicating that it develops the highest strength among the three samples.

Curing and Physical and Mechanical Properties in the Hardened State

Samples produced with water contents of 17%, 22%, and 29% were placed in a curing environment for short- and long-term physical testing. The samples were removed from the molds on the 7th day and stored at 25±5 °C and 60±5% relative humidity for 28 days for short-term initial measurements and for 365 days for long-term second measurements.

The physical properties of the hardened samples with water contents of 17%, 22%, and 29% were determined on the 28th day. Then the samples with %29 water content was tested on the 365th day for the long-term physical properties.

To determine the physical properties of the hardened mortar samples, specific weights, bulk densities, compactness-porosity characteristics, water absorption by weight and volume, capillary water absorption, and solubility effects in water were examined.

In the water absorption tests by weight and volume, the samples were initially saturated in water. However, due to the original material dissolving in water, the samples were kept at 20±5 °C and 90±5% relative humidity until they reached a constant weight, and the tests were conducted with moisture-saturated samples.

To determine the mechanical properties of the original materials, short- and long-term compressive strength and flexural-tensile strength tests were performed. The short-term tests were conducted on the 28th day, while the long-term tests were performed on the 180th day. All tests were conducted with a minimum of three samples. Accordingly, the physical and mechanical properties of the original soil material are provided in Table 8.

RESULTS AND DISCUSSION

The materials used in the original flat earthen roofs of Kemaliye houses (yas-kuru soil, gavcin soil, and Rıhtım stone) have been investigated, and the material properties have been determined. The internal structural properties of the original building materials were examined through analyses conducted at Istanbul University Cerrahpaşa Faculty of Engineering. Upon reviewing the experimental results, it was found that the Rıhtım stone is a limestone that rarely contains quartz sand grains and very little clay; the gavcin soil is primarily a clayey sand that contains a significant amount of calcite, along with plate silicate and clay minerals such as illite and chlorite. The yaskuru-2 sample was found to be a clayey sand that generally contains clay minerals and, to a lesser extent, calcite and quartz.

Granulometric and hydrometer analyses conducted on the original materials classified gavcin soil as clayey sand, yaskuru-1 soil as sand, and yaskuru-2 soil as clayey sand. The results of the bulk unit weight test for the dry soils, presented in Table 5, indicate that the bulk unit weight of the yaskuru soils is lower than that of the gavcin soil. Furthermore, an examination of the plasticity limits shown in Table 5 suggests that the gavcin soil is likely to have fewer water-related structural issues than the yaskuru-2 soil due to its low plasticity index. The plasticity limits for the yaskuru-1 soil could not be determined due to its very high sand content.

In the study, mortar samples were produced with different water contents using the gavcin soil, and the fresh material properties were also examined. Accordingly, the sample with the highest water content exhibited the largest spread diameter and the highest bulk unit weight (Table 8). When the consistencies of the original materials were analyzed (Table 7), it was observed that the sample with 22% water content achieved consistency on the third day, while the sample with 17% water content reached consistency on the second day. Considering the bulk unit weight and specific weight tests conducted on the original materials on the 28th day, it was noted that the highest bulk unit weight value was found in the sample with 17% water content (2.0), while the lowest value was recorded in the sample with 29% water content (1.8). The highest specific weight value was observed in the sample with 29% water content (2.7), whereas the lowest values were 2.6 for the samples with 17% and 22% water contents. The results show that using less water generally helped the samples pack together tighter, leaving fewer air pockets inside. This was further supported by our density and porosity tests that indicated that the structures were denser at lower water levels. But there was a catch: the sample with 17% water, in fact, had more air pockets than the 22% sample, and that tells us that 17% water just wasn't enough to get the ingredients to blend smoothly. By 28 days, we noticed that samples with higher water content absorbed less moisture overall, but they did suck water faster by capillary action (Table 8). Finally, the comparison of 28 days and 365 days results showed that the internal air pockets of the materials naturally shrunk as a whole year passed, so they became tighter over time. This long-term densification was also supported by compactness and porosity measurements. In parallel, both volumetric and gravimetric water absorption values decreased, whereas capillary water absorption increased [13,14]

When placed in water, every single sample dissolved in under an hour, so it was obvious that these raw materials simply cannot withstand direct water contact. So we tested their bending strength and crushing strength at 28 days and 180 days to see how strong they actually were. The mixture with 17% water was the most potent at day 180 (Table 8). This means that over time, the small air spaces inside the material close up, helping it to pack tighter and become much stronger.

CONCLUSION

This research aimed to analyze the traditional flat earthen roof structures anad its materials. As the material tests of original yas-kuru soil, gavcin soil and Rıhtım stone of Kemaliye surroundings were conducted we gained knowledge about the traditional building techniques of flat eartjhen roofs of Traditional Kemaliye houses.

Analyses showed that Rıhtım stone is composed mostly of limestone without clay, and on the other hand, gavcin soil is a clayey sand filled with calcite and clay minerals. In contrast, the yas-kuru soils differed, with yaskuru-2 containing significantly more clay. In our tests for texture and flexibility, the differences were very clear. Gavcin soil is less stretchy and denser than yas-kuru soils, which is why it doesn't warp or shrink as much when it gets wet, but we couldn't even measure the flexibility of yaskuru-1 because it is so sandy, which proves it serves a completely different purpose in the roof.

Finally, the tests on the gavcin mortar showed that the water content has a huge, but tricky, effect on the behavior of the wet mix, how well it packs down, and the strength development over time. More water makes the mix easy to spread but leaves behind air pockets and lowers its density, while less water makes a tighter structure. However, there's a distinct sweet spot, as going too dry, like at 17%, keeps the ingredients from blending evenly, even if it technically ends up strong in the long run. Over time, all mixtures exhibited decreasing void ratios and porosity alongside increases in both bending and compressive strengths, reaching approximately 2.7–3.7 N/mm² after 180 days.

Water-related tests showed that although the material itself is highly vulnerable to direct water exposure—evidenced by rapid dissolution in immersion tests—this apparent weakness is effectively mitigated in real roof applications. Capillary absorption, gravimetric, and volumetric water absorption results collectively indicate that moisture sensitivity at the material scale is counterbalanced by long-term densification, compaction, and, critically, by the layered roof configuration and traditional construction details. In short, making a roof last isn't just about using water-resistant materials. It actually comes down to how well everything works together—from the qualities of the materials themselves to how well the roof is sealed, how moisture is controlled, and how carefully the details are designed.

The results show that long term durability of Kemaliye earth roofs is not a matter of one single element but the whole system works as a team. This study provides us with a solid, scientific roadmap for the preservation and restoration of this unique architectural heritage. It also provides useful insights into the construction of durable, eco-friendly and weather resistant earth roofs in contemporary architecture.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors 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 declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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