[Architecture and Planning Journal (APJ)](https://digitalcommons.bau.edu.lb/apj)

Volume 28 Issue 3 *ASCAAD 2022 - Architecture in the Age of the Metaverse – Opportunities and Potentials*
ISSN: 2789-8547

Article 34

March 2023

MOISTURE-HARVESTING LIZARD SKINS AS AN INSPIRATON FOR PERFORMATIVE BUILDING ENVELOPES IN ARID CLIMATES

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Abstract

Research on shape-shifting adaptive architectural skins has recently focused on bio-inspired programmable materials. Only a few studies however examine the microstructure of living organisms, especially in terms of morphological adaptation in harsh climatic conditions. This paper explores the microstructure of moisture-harvesting lizard skins, specifically the Trapelus species of the Agamidae family in North-East Africa, as an inspiration for programmable materials in adaptive building skins in the arid climate of Egypt. The paper investigates the ability to improve the durability and morphological capabilities of programmable materials based on surface formation, utilizing digital fabrication techniques. A series of physical experiments were conducted on different samples of 3D printed wood filament under several humidity conditions, as a single layer, with textured patterns, and with the addition of potassium chloride as a moisture-harvesting chemical composite. The paper concluded that materials composed of textured patterns and moisture-harvesting chemical composites exhibited the highest moisture retention, therefore leading to advantages in its use in adaptive building skins in arid climates, through a wide variety of design possibilities for performative building envelopes.

Keywords

Programmable materials, adaptive building skins, hygroscopy, moisture harvesting lizard skins.

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ABSTRACT

Research on shape-shifting adaptive architectural skins has recently focused on bio-inspired programmable materials. Only a few studies however examine the microstructure of living organisms, especially in terms of morphological adaptation in harsh climatic conditions. This paper explores the microstructure of moisture-harvesting lizard skins, specifically the Trapelus species of the Agamidae family in North-East Africa, as an inspiration for programmable materials in adaptive building skins in the arid climate of Egypt. The paper investigates the ability to improve the durability and morphological capabilities of programmable materials based on surface formation, utilizing digital fabrication techniques. A series of physical experiments were conducted on different samples of 3D printed wood filament under several humidity conditions, as a single layer, with textured patterns, and with the addition of potassium chloride as a moisture-harvesting chemical composite. The paper concluded that materials composed of textured patterns and moisture-harvesting chemical composites exhibited the highest moisture retention, therefore leading to advantages in its use in adaptive building skins in arid climates, through a wide variety of design possibilities for performative building envelopes.

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ملخص

ركزت الأبحاث التى تتمحور حول أغلفة المبانى المتكيفة المتغيرة الشكل مؤخرًا على المواد القابلة للبرمجة المستوحاة من الطبيعة والكائنات الحية. ومع ذلك، فإن القليل من الدراسات فقط يعمل على دراسة البنية الدقيقة للكائنات الحية، خاصة من حيث التكيف المورفولوجي في الظروف المناخية القاسية. تستكشف هذه الورقة البنية الدقيقة لجلود السحالي التي تحصد الرطوبة ، وتحديداً أنواع "الترابيلوس" من عائلة "أجاميدا" في شمال شرق إفريقيا، كمصدر إلهام للمواد القابلة للبرمجة في جلود البناء التكيفية في المناخ الجاف المميز لبلد مثل مصر. تبحث الدراسة في القدرة على تحسين المتانة والقدرات المورفولوجية للمواد القابلة للبرمجة بناءً على تكوين السطح باستخدام تقنيات التصنيع الرقمي. تم إجراء سلسلة من التجارب الفيزيائية على عينات مختلفة من خيوط الخشب المطبوعة عن طريق تقنية الطباعة ثلاثية الأبعاد في ظروف رطوبة عديدة، متمثلة فى: الطبقة الواحدة، والأنماط المنسوجة، وتلك التى تنتج عن إضافة كلوريد البوتاسيوم كمركب كيميائي لحصاد الرطوبة. وخلصت الورقة البحثية إلى أن المواد المكونة من أنماط منسوجة ومركبات كيميائية لحصاد الرطوبة أظهرت أعلى احتباس للرطوبة، مما أدى إلى مزايا في استخدامها في جلود المباني المتكيفة في المناخات القاحلة، من خلال مجموعة متنوعة من إمكانيات التصميم لأغلفة البناء عالية الأداء.

الكلمات المفتاحية: المواد القابلة للبرمجة، أغلفة البناء المتكيفة، الاسترطاب، جلود السحالى الحاصدة للرطوبة.

1. INTRODUCTION

The latest software and hardware developments in the use of programmable materials in advanced manufacturing processes and workflows have demonstrated several new possibilities for the design and morphology of architectural shape-shifting systems. The ability of certain materials to change shape based on external climatic stimuli such as hygromorphic materials that react to humidity, and thermo-bimetals that react to temperature, has allowed for naturally actuated shape-shifting and self-assembling systems. In our previous research on generating different morphological transformations using the hygroscopic properties of wood (El-Dabaa and Abdelmohsen, 2020; Ibrahim et al., 2020a; Ibrahim et al., 2020b; Aly et al., 2021; El-Dabaa and Abdelmohsen, 2022; Ibrahim et al., 2022), we develop systems that use motion grammars to computationally simulate such transformations that are induced by the deformation of wood as a natural material.

Similar studies have attempted to develop bio-inspired programmable materials and architectural shape-shifting systems (Vazquez et al., 2019). However, very few studies examine the microstructure of living organisms, specifically in relation to their morphological adaptation in harsh climatic conditions. This paper explores the microstructure of moisture-harvesting lizards (Comanns, 2011), specifically the Trapelus Mutabilis and Trapelus Pallidus species of the Agamidae family in North-East Africa (Vesely and Modry, 2002), as an inspiration for programmable materials in adaptive building skins in the arid climate of Egypt.

The paper first explores the geometrical and structural configuration of the Trapelus species, and the different morphological patterns, densities, and protective skin abilities afforded by the size, shape, and relative position of microstructures on its integument (Yenmiş, 2021). A wide range of design possibilities for adaptive building skins are deduced accordingly, with focus on the variety of identified actuation mechanisms such as twisting, twirling, and bending.

Second, the paper explores the adaptation of the lizard species' skin structure to different climatic conditions and its ability to harvest moisture in order to determine the impact on water transfer and wettability. An investigation of the lizard's skin microstructure is conducted (Comanns et al., 2014), including a biomimetic analysis of its semi-tubular longitudinal and latitudinal channels, and the uptake of moisture through its harvesting behavior process. By means of a comparative analysis between planar surface formations and the lizard species' skin formations that consist of a variety of surface extrusions and protrusions (Yenmiş, 2021), the paper concludes different hygroscopically informed morphological characteristics related to retaining water for long durations.

The paper then develops a computational approach to emulate the adaptive and moisture-harvesting properties of the Trapelus species (Yenmis et al., 2016) for adaptive architectural skins. A test case in Cairo, Egypt is used to explore specific parameters and rules for the design and form generation of an adaptive architectural skin in a hot arid environment using Rhino and Grasshopper. By mimicking the lizard species' skin moisture harvesting techniques, a series of design iterations are developed that achieve a variety of morphological transformations and responses under varied environmental stimuli. The results are simulated using performative plugins on Grasshopper to test the environmental performance of the generated iterations and achieve optimal levels of adaptation and durability.

2. MIMICKING LIZARD SKIN

2.1. Lizard Skins and their Morphological Systems

The remarkable ability of moisture-harvesting lizards to live in arid environments is demonstrated by different lizards. Lizards exhibit a unique physical property and ability to absorb water by capillarity and carry it for ingestion due to specific skin characteristics. These characteristics include a micro-structured skin featuring capillary tubes between irregular overlapping patterns that facilitate passive and occasionally directed transfer of the collected water. The ecological function of this system is the absorption of water from various sources (Comanns et al., 2016).

The increased wettability of the lizard integument is known as hydrophilicity, which is brought on by chemical characteristics and frequently occurs in conjunction with specific microstructures, as shown in Table 1. Several species of desert lizards belonging to the

Phrynosoma, Phrynocephalus, Trapelus, Moloch, Pogona, Cordylus, and Uromastix genres have been shown to passively absorb water from their surroundings.

Table 1: Classification of different wetting behaviour based on different angles and microstructures of lizards (Comanns P. 2016)

classification	wetting behavior	required topography
$0° \leq \theta < 10°$	superhydrophilic	only on rough or structured surfaces
$10° \leq \theta < 90°$	hydrophilic	also on smooth surfaces
$90° \leq \theta < 120°$	hydrophobic	also on smooth surfaces
$120° \leq \theta < 150°$	hydrophobic	only on rough or structured surfaces
$150° \leq \theta < 180°$	superhydrophobic	only on rough or structured surfaces

Different types of the Trapelus Pallidus lizard species display the behaviour of rain-harvesting (Vesely & Modry, 2002), as shown in Figure 1. The species under study are the Trapelus Mutabilis and Trapelus Pallidus species which are from the Agamidae family that is located in arid regions in Egypt (Yenmiş, 2021).

Fig.1: Rain-harvesting posture of the female Trapelus Pallidus (Vesely & Modry, 2002)

The geometrical and structural dimension of such lizard species is accompanied by specific morphological capabilities and potentials, as lizard bodies and skins are covered wholly with different densities and pattern variations. These patterns have different sizes, shapes, and relative positions that vary to facilitate the desired motion of the lizard as well as providing a protective skin. Several biomimetic techniques have been developed to mimic this actuation system utilizing different parameters regarding densities, position, and geometrical shape (Yenmiş, 2021), and to demonstrate the adaptation of lizard skin structures to technical applications (Comanns et al., 2014), as the skin's ability to harvest moisture impacts wettability and water transfer.

2.2. Microscopic Views

The microstructure of lizard skins is generally known to contain semi-tubular channels in both longitudinal and latitudinal directions. This geometrical configuration enhances the skin to uptake more moisture through the harvesting behaviour process (Yenmiş, 2021). The inner surfaces of the semi-tubular, hinge-joint system's expanded cavity through which the water enters are in contact with fragmented surfaces. Water fills the hinge-joint channels as capillary action draws it down the scale hinge holes, where the greater surface area of the enlarged and convoluted hinge-joint enhances the attracting interactions between the surfaces and water, as shown in Figure 2 (Sherbrooke et al., 2007).

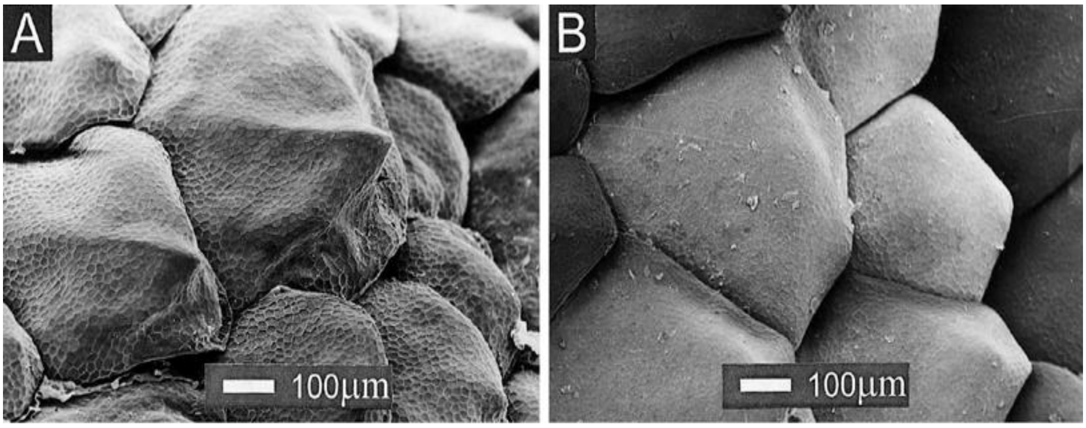


Fig.2: Electron photomicrograph scan of the surface of (A) Trapelus pallidus and (B) Trapelus ruderatus (Vesely & Modry, 2002)

The dispersion of water through several channels across the complete branching network of semi-tubular hinge-joint channels may increase the speed at which water is transported. Water may travel from the lizard body contact surfaces to the head via capillary forces in resistance to the force of gravity (Sherbrooke et al., 2007). In terms of wetting, depending on surface structure and roughness, each liquid-material interaction leads to a different wetting phenomenon, as shown in Figure 3 (Comanns, 2016).

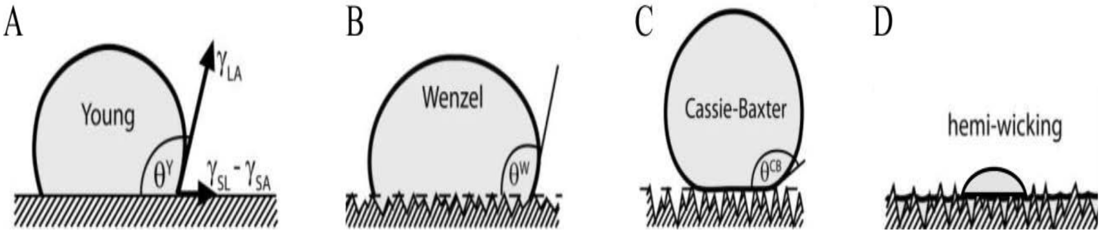


Fig.3: Wetting phenomenon model mentioned by A) Young model, B) Wenzel, C) Cassie-Baxter, and D) hemi-wicking (Comanns, 2016)

2.3. Moisture-Harvesting Process in Material Composites

In arid areas, the extraction of water from air is a promising method of supplying water. Desiccant materials, which can attract and retain moisture, can help achieve this process, guided by moisture-harvesting activities and processes in lizard species as an inspiration (Kallenberger & Fröba, 2018). To improve the material moisture absorption capability and process of humidity retention, chemical composites and components are applied to catalyze these processes. One of the chemical composites that are significantly known to retain moisture for long duration is Potassium Chloride (*KCl*). The hygroscopic growth factors of potassium chloride against water activity are mapped in Figure 4 (Jing et al., 2017). In the next section, the paper investigates the incorporation of potassium chloride as an additive to 3D printed samples to test the hygroscopic properties of the composite, based on lessons learned from the microstructure and moisture-harvesting properties of lizard skins.

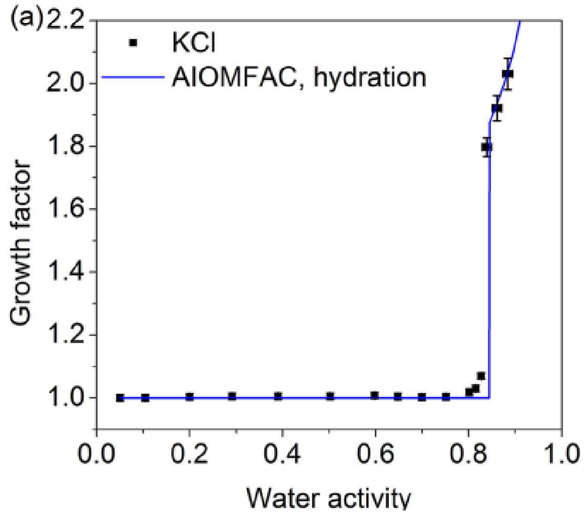


Fig.4: Graph of hygroscopic growth of potassium chloride against water activity (Jing et al., 2017)

3. COMPUTATIONAL IMPLEMENTATION

3.1. Physical Experiments

Based on studying the microscopic structure of moisture-harvesting lizard skins, the paper explores the testing of composite materials that mimic this moisture-harvesting behavior. The first phase of this testing implemented physical testing or experimentation of different materials under different humidity conditions. This was conducted using a transparent humidity chamber utilizing specific equipment, including a humidifier, dehumidifier, glue, and a hygrometer.

The samples under study included primarily 3D printed wood due to its hygroscopic properties related to shrinking and swelling based on varying humidity conditions. Wood filaments (40% wood, 60% PLA) were 3D printed for the purpose of this experiment, using a 0.8mm thick nozzle. Three samples with dimensions 5cm x 10cm were tested. These included: (1) a single plain unit, (2) a single unit with extrusion patterns, and (3) a single unit with extruded pattern and filled with potassium chloride. The three samples were tested in a humidity chamber with dimensions 50cm x 50cm x 80cm, which consisted of a humidifier and de-humidifier to apply and vary specific humidity conditions throughout the experiment.

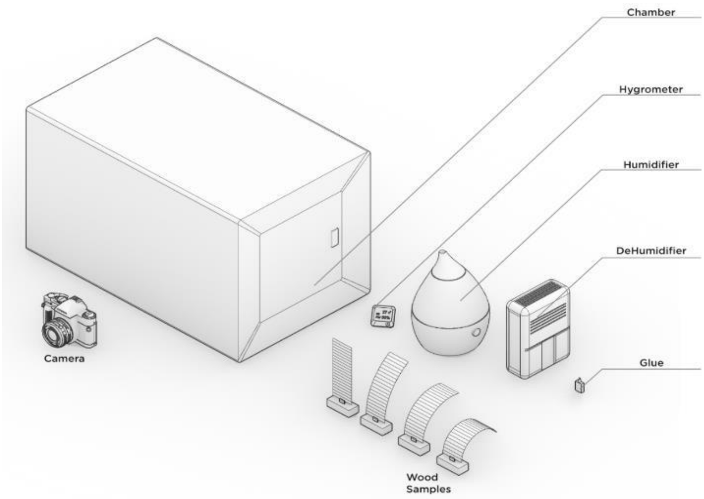
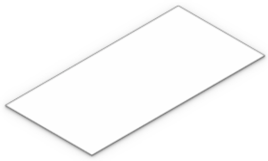
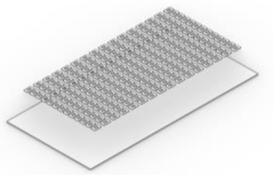
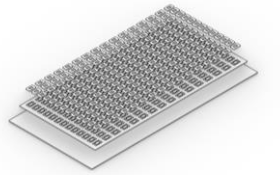


Fig.5: Setup of the physical experiment under different humidity conditions for multiple wood filament 3D printed samples

The experiment started off by designing the samples using 3D modeling tools (including Rhinoceros & Grasshopper 3D). Multiple designs with multiple considerations were developed based on patterns that were seen to mimic the morphological configuration and process inspired by the lizard skin, specifically the Trapelus species. The three types of material compositions were then compared. Based on the results, the input parameters were concluded to identify the suitable parameters to reach a specific design consideration. The three samples under study are shown in Table 2.

Table 2: Details of the three tested samples

3D Printed - Single Layer	3D Printed - Pattern Layer	3D Printed – Potassium Chloride Layer
		
Layer 1: 3D printed wood filament	Layer 1: 3D printed wood filament Layer 2: Extruded immersed pattern	Layer 1: 3D printed wood filament Layer 2 & 3: Extruded pattern immersed filled with potassium chloride

The selected designs were then imported into the *Cura* open-source slicing application for 3D printers to prepare the samples for 3D printing. Several parameters were adjusted, including layer height, number of layers, direction of printing, and temperature. Upon fabrication of the three designs, the samples were tested together under the same humidity conditions. Figure 6 shows the outcome of the 3D printing for the three wood filament samples.

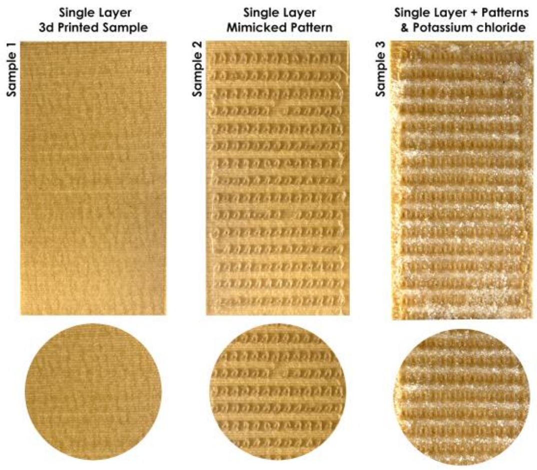


Fig.6: Fabricated samples prepared for the experiment

The response behavior of three samples was then tracked and analyzed, following the validated physical experimental study for shape-shifting materials by Grönquist et al. (2018) and Menges et al. (2014), and the validated *Kinovea* image analysis software for measuring angles of curvature by Puig-Diví et al. (2017). Based on both methods, the effect of each design parameter on the angle of curvature was measured for each sample when exposed to variation in humidity (El-Dabaa and Abdelmohsen, 2020). Figure 7 shows an example of the material motion during the experiment.

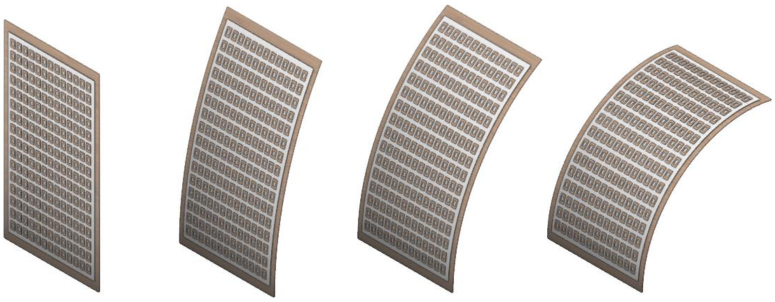


Fig.7: Material motion during the experiment

After each stage of the experiment, the motion for each of the samples was documented through multiple photographic images, and the angle of deflection was measured using the Kinovea software. In the first stage of the experiment, the samples reacted gradually to room humidity (54%) by an angle of deflection of 3˚ only. After one hour, while increasing the humidity to 83%, the angles of deflection gradually increased for each of the samples. The angle of deflection for sample 1 (single layer) was recorded at 8˚. Sample 2 (with extruded immersed) pattern was shown to retain more humidity due to the surface pattern, where the angle of deflection was recorded at 11˚. Sample 3 (with extruded immersed pattern and potassium chloride) exhibited an angle of deflection of 7˚ due to absorption. After finalizing the experiment and observing the samples for a total of 5 hours, Sample 1 and Sample 2 were shown to return gradually to their initial shape, while Sample 3 was shown to react to the humidity absorbed by the composite and exhibit the largest angle of deflection (39˚). Figure 8 shows the different motion responses and angles of deflection for each of the three samples upon the start of the experiment, after 1 hour, and after concluding the experiment after 5 hours respectively.

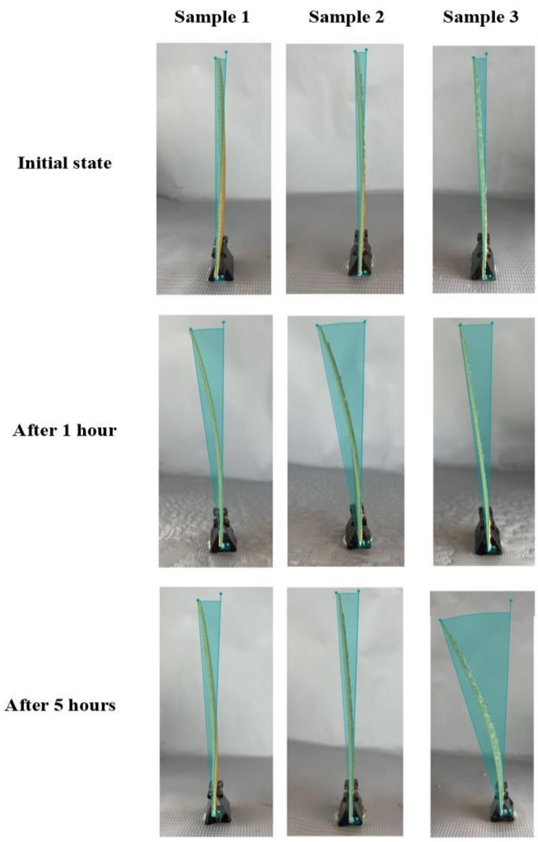


Fig.8: Motion responses and angles of deflection recorded for the three samples using physical experiments and Kinovea image analysis software

3.2. Simulation

Based on the previous experimentations, it was observed that the mimicked geometrical sample with surface extrusion and capillary protrusions with chemical composite embedded retainer, which was inspired by moisture-harvesting lizard skins, could absorb percentages of moisture from external stimuli. An annual humidity analysis for the Sinai desert region in Egypt, specifically the city of Ras Sedr, shows an increasing level of humidity at night more than day hours, as shown in Figure 9. This indicates that the material can retain humidity at night times to influence its morphological ability and programmed transformation stability during the hot day time.

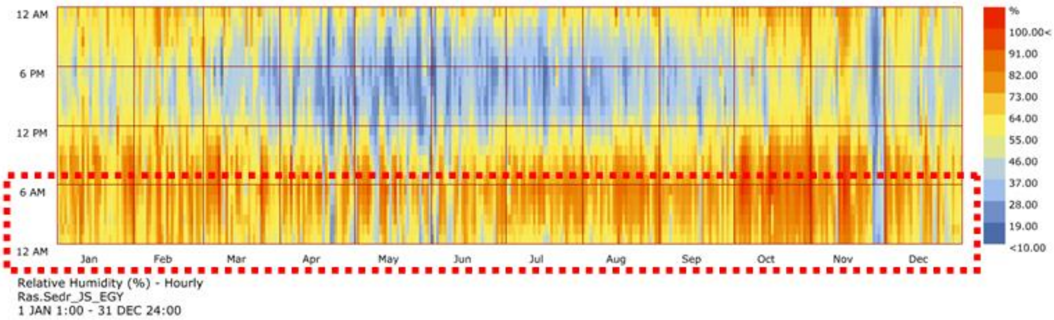


Fig.9: Humidity levels using Grasshopper and Ladybug plugin for the city of Ras Sedr (desert region of Sinai, Egypt)

3.3. Design Considerations for Building Envelopes

The previous studies and experiments demonstrate the manipulation of design decisions toward improving building performance. Façade skins can be programmed based on multiple parameters. One of the parameters studied is the surface design element that affects the time and type of motion response to external stimuli and weather conditions. It was also shown that the amount and type of embedded chemical composites (such as KCl) are considered to control the amount of absorbed moisture and the duration of moisture retention that directly impacts the time of morphological transformation of the material of the building skin. Each panel of the skin can be programmed with a specific morphology based on the amount of optimized temperature and illumination. Figure 10 shows a sunlight hour analysis and radiation analysis for a sample designed building skin throughout the year.

DOI: 10.54729/2789-8547.1229

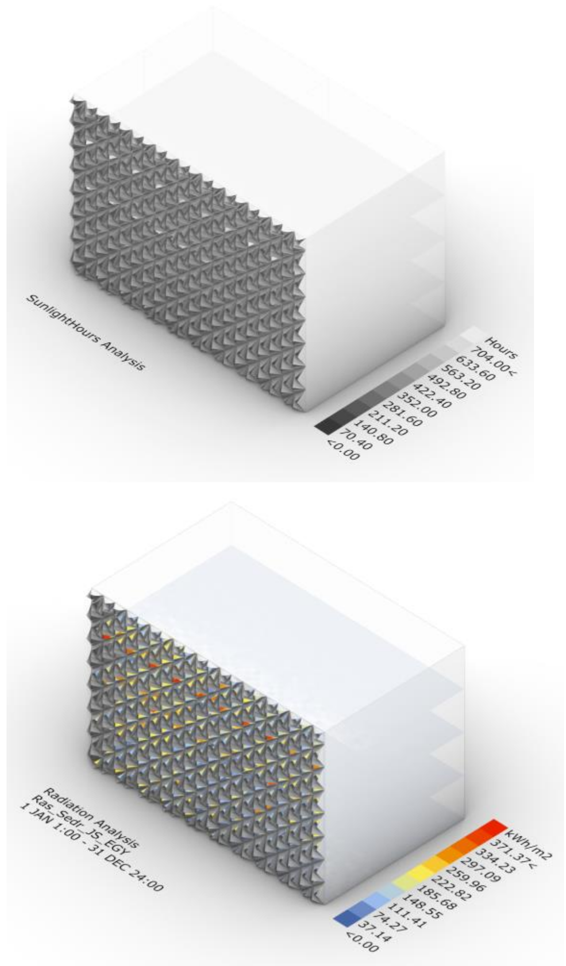


Fig.10: Sunlight hour analysis and radiation analysis for a sample designed building envelope during the year

4. DISCUSSION

From the previous experiment, it was observed that the 3D printed samples using wood filament retained their initial state after decreasing humidity. The single layer plain sample was exposed to external stimuli, and its surface was directly influenced by humidity. This sample reacted gradually based on the layer thickness and direction of printing. This planar texture surface allowed the material to dry faster. The material absorption varied from one geometry to another due to the surface formation.

The sample with the extrusion patterns reacted to humidity faster due to having a larger number of channels, leading to higher humidity retention. The potassium chloride composite was shown to exhibit a higher ability to retain humidity due to the chemical capability of the composite to retain moisture for a long time. In this case, a significantly larger deflection was recorded, owing to both extrusion patterns and texturing on the one hand, and the high humidity retention property of the chemical composite on the other. This moisture-harvesting inspired process opens new possibilities for design and for tailored morphological compositions and configurations in adaptive building skins.

5. CONCLUSION

This paper investigated the ability to improve the durability and morphological capabilities of programmable materials based on surface formation, utilizing digital fabrication techniques. The study aimed to translate the biological formation of skins of lizard species residing in arid regions into geometry and material composition. The process of mimicking morphological complexity and humidity retention in lizard skins was used to inform a digital workflow from inspiration to fabrication stage. 3D printing techniques were shown to produce more design variations and possibilities, allowing for simulating and programming material motion for building envelopes.

The research concluded that the materials of single layer plain surfaces react directly to humidity with minimal ability to retain moisture. Materials composed of textured and patterned surfaces containing extrusions and channels were shown to retain more moisture, therefore impacting the morphological capabilities of the material. It was also shown that utilizing chemical composites on top of these textured layers was highly significant in the process of moisture retention. The sample building envelope design that used potassium chloride acts better due to the ability of the composite to absorb moisture while exposed to humidity and releasing it gradually, giving it an edge in terms of moisture retention in adaptive building envelopes in arid climates.

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