Biomimicry-Based Materials

Subjects: Construction & Building Technology | Engineering, Manufacturing | Engineering, Civil
Contributor: Maria De Los Ángeles Ortega Del Rosario , Kimberly Beermann , Miguel Chen Austin

Biomimicry as a tool in architecture and building construction offers the opportunity to inspire active envelopes and integrate natural concepts and principles aiming for sustainable and climate responses.

energy | water | hydrophobicity | material | biomimicry | manufacturing | additive manufacturing | composites

1. Hydrophobic Materials

Hydrophobicity in materials and coatings is an attractive property in which biomimicry-based approaches have been actively used lately. Moisture and other sources of water may penetrate and react with the surfaces causing degradation due to corrosion, alkali–aggregate reactions, sealant failure, wind-induced delamination, freezing and thawing, sulfate attack, mold growth, wood decay, loss of thermal resistance of insulation, crack propagation, and water leakage, among others [1][2][3]. Several plants and animals' skins have served as a source of inspiration to achieve this behavior. For instance, lotus leaves have a hydrophobic surface that repels water droplets, also exhibiting a self-cleaning ability due to having a contact angle > 150°. These properties can be exploited as biomimetic coatings in infrastructures.

Recently, Collins and Safiuddin [1] gathered a collection of materials that have been used as biomimetic coating materials, such as polydimethylsiloxane (PDMS), with a contact angle close to 170°; ultrafine powder coating (UPC), with a contact angle superior to 160°; carbon nanotubes (CNT), nickel (Ni), Ni/Nano-C, and Ni/Nano-Cu, with a contact angle of 155.5°; fluoro-octyl-trichloro-silane-titanium; Janus particles; diamond-like carbon; graphene oxide-silica (GO-SiO_2); calcium hydroxide [$Ca(OH)_2$]; Photopolymer (PP); Acrylic polymer (AP); antimony doped tin oxide/polyurethane (ATO/PU) film; PMMA (Polymethyl methacrylate); PPS/PTFE (Polyphenylene sulfide/polytetrafluoroethylene); copper (Cu); and zinc oxide (ZnO) films. One can find among their properties anti-corrosive behavior, dust-free behavior, anti-abrasion, self-cleaning, anti-fogging and anti-icing, and lubricant and surface coating capabilities. The authors suggested that applications such as buildings, bridges, pavements, and sewers can benefit from these properties. Regarding the buildings, these properties could improve drainage systems, performing as a dust-free, self-cleaning surface on envelopes, preventing the growth of molds and algae, and therefore increasing the service life of buildings. In the study developed by Ghasemlou et al. [4], the authors proposed the use of low-cost raw materials, such as poly(dimethylsiloxane) (PDMS), ternary starch/PHU/CNC (SPC), silica nanoparticles (SNPs), and vinyltriethoxysilane (VTES) to develop artificial robust superhydrophobic surfaces inspired by the lotus leaf (*Nelumbo nucifera)* from Melbourne, Australia. Moreover, Caldas et al. [5] used titanium dioxide nanocoating on a steel welding sheet surface to develop a fog harvesting system for building envelopes. The metal surface was spray painted with a high emissivity white paint (emissivity between 0.989 and 0.992). In this case, the titanium dioxide-based coating performed strong hydrophilicity under ultra-violet (UV) irradiation and strong hydrophobicity in dark conditions.

Silica (SiO_2) nanofibers and cellulose nanofibers (CNF) were synthesized into a dual fibrous aerogel with a honeycomb-like cellular structure and a nanofiber/nanonet composite cell wall by freeze-drying in [6]. Tetraethoxysilane and poly (vinyl alcohol) were used as starting materials to obtain the SiO_2 nanofibers.

2. Self-Healing Materials

The self-healing capacity of living organisms is fascinating and resourceful. It is commonly observed in several cells and tissues, such as bone tissues, skin, and blood [7]. Regarding building envelope applications, this approach has been explored with self-healing concretes. Self-healing concrete is defined by Zhang et al. [8] as “a concrete composite with the ability to repair small cracks automatically, without any external diagnosis or human intervention.” They are of interest in responsive envelopes since they present the ability to adapt and respond to the environment. Additionally, concrete is the most used construction material nowadays; thus, achieving self-healing properties is of great interest [8][9]. These materials can be divided into autogenous healing and autonomous healing. The healing process in the former comes from the material itself, while the latter needs a trigger to activate the process. Autogenous healing is the result of several phases coexisting within the concrete. After the hardening process of the concrete, non-hydrated phases can appear. For instance, a non-hydrated clinker phase (tricalcium silicate, C_3S, and dicalcium silicate, C_2S) may react with the water that enters the structure through the cracks and produce calcium-silicate-hydrate. In addition, portlandite ($Ca(OH)_2$) can react with the carbon dioxide dissolved in the water, producing some space-filling minerals [7]. According to [9], even if this autogenous healing is useful, the cases studied show limitations and unreliability in the long term.

Moreover, Zhang et al. [8] state that some biomimetic approaches can serve as triggers or mechanisms in autonomous healing, such as electrodeposition technology and embedding shape memory alloy (SMA), capsule, vascular, or bacteria in concrete [9].

Bacteria use or bio-healing is a widely used approach in which the bacteria convert water and some food source, usually added into the concrete matrix, releasing calcium carbonate as a metabolic byproduct and sealing the cracks in the concrete. Even if using bacteria to develop self-healing concrete is not considered a biomimicry-based solution, it is indeed considered in previous works as a bioinspired approach [10][11]. Furthermore, they show the potential to fabricate resilient materials and infrastructures [8].

3. Biomineralized and Natural Materials

Jia et al. [12] developed an exhaustive review of biomineralized materials that can serve to deeply understand biological hierarchical 3D material architecture as a guide to understanding biological structures. The authors proposed for mineral building blocks 0D granular-shaped, 1D fiber-shaped, 2D tablet/laminated-shaped, and 3D biocontinuous/porous-shaped motifs based on their geometrical features. These kinds of materials exhibit mechanical properties, especially regarding fracture toughness, that make them suitable for biomimicry approaches in architecture [13].

In the study of Sanga et al. [14], clay bricks were developed by mimicking termites' technique to naturally cemented mound structures. Termites usually feed on cellulose-based materials. To create their shelter, they build above or underneath the ground, changing the soil structure by adding saliva containing mucopolysaccharides which present the cellulase enzyme, converting this cellulose into simple glucose. During this process, and before breaking into glucose, this cellulose is digested into shorter polysaccharides and oligosaccharides. They act as soil stabilizers and binders [15]. Here, the authors used cold-water soluble cassava flour instead of cellulose, and two types of soils were collected from the southern zone of Tanzania. Pure cassava flour, indirectly heated to increase viscosity and cohesion, distilled water, and clay soil were hand mixed and sampled in the form of bricks. The samples were left in the molds for three days and then left to air-dry for twenty-eight days. Their results showed that a cassava paste beyond 6% added to wet soil caused cracking and the development of fungi around the brick surface, but if maintained at 1.6%, a better strength performance can be achieved when compared to traditionally kiln-fired clay bricks.

4. Composite and Smart Materials

When using composite materials, material testing, design, and fabrications are all considered together since the composite properties, contrary to other raw materials, depend on the nature of their constituents, the proportion, and the fiber's orientation, as well as the fabrication process. Composite materials such as fiber-reinforced polymers (FRP), glass-fiber polymers (GRP), some metal composites, and concrete composites play a vital role in developing biomimetic envelopes and structures [16]. Thus, material design and fabrication must work together to adapt biomimicry-based approaches to responsive envelopes.

The ITECH Research Demonstrator 2018–19 [17] is one case in which composite materials have been adapted to biomimicry-based envelopes. The kinematic and folding behaviors of the ladybug's (*Coleoptera coccinellidae*) hindwings were a source of inspiration for developing two compliant elements. Here, an industrial robotic tape-laying process was used to fabricate laminates composed of fiber-reinforced plastic. Composite material properties are highly dependent on the fiber direction. Then, this process allowed them to adjust the fiber orientation and material properties precisely. They were able to process the carbon fiber tapes; however, in the case of the glass-fiber tapes, they had to be processed manually.

Similarly, a smart and adaptive outer facade shading system was developed by Körner et al. [18], inspired by the hinge-less motion of the underwater snap-trap of the carnivorous waterwheel plant (*Aldrovanda vesiculosa*). The design objective was to minimize the bending stresses within the hinge zone. Thus, the materials were tested, focusing on the flexible hinge-zone. A vacuum-assisted process (VAP) was used to fabricate a structure composed of woven glass-fiber fabric, epoxy resin, and polyvinyl chloride (PVC) laminating foil. A material set-up was used to determine the influence of fiber orientation and the implementation of the PVC foil within the composite on the bending stiffness of the hinge-zone. The BUGA fiber pavilion at Heilbronn, Germany [19] is another biomimetic case in which carbon and glass fiber composites were used as the constituent of a composite material. The aim was to construct a bone-like lightweight dome. Core filament winding and robotic fabrication were used as manufacturing techniques to obtain the composite material.

Moreover, these principles applied to fibrous polymeric composites can be applied to other materials. For instance, Allameh et al. [20] developed a nacre-inspired concrete reinforced with chopped fiberglass and chopped carbon fiber and a matrix consisting of masonry cement and graded sand (Quikrete® 1102) to enhance the brittle property exhibited by traditional concretes in construction. The biomimicked composites were achieved by using 3M spray adhesive 80 as a soft polymer. The authors proposed this as a means to endure the effects of earthquakes. This material was possible by using an additive manufacturing technique of concrete deposition, increasing toughness.

The Bouligand structure in the dactyl club of mantis shrimp bioinspired a helicoidal printing pattern in the studies of Liu et al. [21]. The mixture was based on cementitious materials such as general-purpose cement, 30 wt% of ground granulated blast-furnace slag, and 25 wt% of silica fumes. Natural river sand was added as aggregate, and in some specimens, steel fibers were added to make a fiber-reinforced mixture. The existence of these fibers and their orientation changed the results on the specimens regarding energy absorption, peak impact force, impact duration, and porosity. Concrete tiles were developed inspired by animal fur to achieve better insulation performance by Hershcovich et al. [22] and to achieve evaporative cooling mimicking the elephant's wrinkles by Peeks and Badarnah [23]. The compressive, flexural, and bonding strength of concrete matrices have been widely studied, especially for casted concrete. However, when this material is used to fabricate structures by using additive manufacturing techniques, in some cases, the material stacking is made layer-by-layer, resulting in mechanical anisotropy, void development that weakens interfaces, and a high need for a thorough design process to achieve the desired results.

A material that has gained much interest recently regarding the use of AM in construction is clay. The literature shows that it can be very well-adapted to uses such as non-structural blocks and partitions, components for shades and linings, and non-structural brick vaults [24]. In addition to this, they have gained ground against the common use of concrete since the latter currently presents significant challenges to be compatible with the sustainability and resilience necessary in cities [25]. Various studies have addressed the sustainability of clay [26][27][28] and its capacity to generate resilience against disasters [29][30].

Termite mound soils have been widely used in the past as construction materials for bricks. However, a major challenge with these materials is their limited availability. Thus, Sanga et al. [14] used termite mechanisms to produce their mound soil as a biomimicry-inspired strategy to produce alternative clay bricks. Clay may also be used as a biomimetic coating material. In the case of Mu et al. [31], biomimetic superhydrophobic cobalt blue/clay mineral hybrid pigments were produced, which can act as a self-cleaning, anticorrosive surface. In Dong and Zhang [32] the authors proposed superamphiphobic coating-based nanoclays with fibrous, plate-like, and porous microstructures. They suggested that these developments may help in developing anti-wetting coatings.

Bimetals and metal composite alloys have been adapted in several applications due to their capabilities to respond to thermal stimuli. In the case of [33], the *Ammophila arenaria* leaf-rolling was mimicked by using bimetals that responded to temperature variation and solar radiation, conceiving a future proposal of responsive envelopes. Furthermore, in Charpentier et al. [34], thermobimetals were used to develop an adaptive shading device that mimicked *nyctinastic* kinetics. However, the authors state some challenges regarding the non-uniformity of the temperature-driven deformation of the bimetal.

Interlocking features are often present in bioinspired structures, such as nacre, bones, dermal-epidermal micro-ridges of human skin [35], beetle's wings [36], the hooks and bulbs of endoparasitic worms, *Pomphorhynchus laevis*, and the alligator gar scales, among others [10][37][38][39]. Interlocking shows mutually dependent interactions between physical objects at their interfaces [39] acting in structures as a toughening mechanism [40]. Therefore, several bioinspired interlocked structures have been developed for different scenarios. They can be classified as static interlocks and regulable interlocks. The former is characterized by enhanced interfacial adhesion, whereas the latter stimulates dynamic responses that lead to multiple functionalities [39]. In this sense, Topologically interlocked materials (TIMs) have recently emerged as a class of architectured materials consisting of stiff building blocks of well-controlled geometries. These structures can slide, rotate, or interlock, collectively providing regulable mechanisms, structural properties, and functionalities [41].

In the works of Srivatsa et al. [37], nacre-bioinspired brick-and-mortar structures of MXene/Polymer nanocomposites were modeled at the microscale using analytical and numerical methods based on finite elements to estimate elastic properties. The design led to an interlocking mechanism between the MXene ($Ti_3C_2T_x$) fillers in the polymeric matrix (epoxy-resin and polyvinyl alcohol (PVA)). This nacre-bioinspired interlocking promoted an effective load transfer from the polymer to MXenes, and a strength and damage resistance, due to an increase of the weight/volume fraction of MXenes. The authors found that these bioinspired designs increased Young's modulus by 25.1% and the elastic stress capacity by 42.3%. The authors suggested that nacred-inspired interlocking mechanisms may help control and optimize structure properties.

Moreover, in the case of Mostert and Kruger [42], topological interlocking was employed as a biomimicry principle to facilitate filament bonding during the deposition in concrete 3D printing. The authors altered the interlayer surface with a cross-sectional square, sinusoidal, and zigzag geometric nozzle to achieve topological interlocking. Their results showed that even if the patterns obtained were not fully interlocked, the interlayer bond strength improved at around 66%, 59%, and 29%, respectively, on the selected nozzle geometries.

References

1. Collins, C.M.; Safiuddin, M. Lotus-Leaf-Inspired Biomimetic Coatings: Different Types, Key Properties, and Applications in Infrastructures. Infrastructures 2022, 7, 46.

2. Chung, D.; Wen, J. Building Envelope Moisture Transport in the Context of Assembly Aging and Uncertainty. Technol. Archit. Des. 2019, 3, 221–233.
3. Recart, C.; Sturts Dossick, C. Hygrothermal Behavior of Post-Retrofit Housing: A Review of the Impacts of the Energy Efficiency Upgrade Strategies. Energy Build. 2022, 262, 112001.
4. Ghasemlou, M.; Le, P.H.; Daver, F.; Murdoch, B.J.; Ivanova, E.P.; Adhikari, B. Robust and Eco-Friendly Superhydrophobic Starch Nanohybrid Materials with Engineered Lotus Leaf Mimetic Multiscale Hierarchical Structures. ACS Appl. Mater. Interfaces 2021, 13, 36558–36573.
5. Caldas, L.; Andaloro, A.; Calafiore, G.; Munechika, K.; Taube, B.; Oliveira, M.; Cabrini, S. Water Harvesting from Fog Using Building Envelopes: Part II. Water Environ. J. 2018, 32, 466–475.
6. Dou, L.; Si, Y.; Yu, J.; Ding, B. Semi-Template Based, Biomimetic-Architectured, and Mechanically Robust Ceramic Nanofibrous Aerogels for Thermal Insulation. Nano Res. 2022, 15, 5581–5589.
7. Shahsavari, R.; Hwang, S.H. Bioinspired Cementitious Materials: Main Strategies, Progress, and Applications. Front. Mater. 2020, 7, 62.
8. Zhang, W.; Zheng, Q.; Ashour, A.; Han, B. Self-Healing Cement Concrete Composites for Resilient Infrastructures: A Review. Compos. Part B Eng. 2020, 189, 107892.
9. Cremaldi, J.C.; Bhushan, B. Bioinspired Self-Healing Materials: Lessons from Nature. Beilstein J. Nanotechnol. 2018, 9, 907–935.
10. Ahamed, M.K.; Wang, H.; Hazell, P.J. From Biology to Biomimicry: Using Nature to Build Better Structures—A Review. Constr. Build. Mater. 2022, 320, 126195.
11. Pacheco-Torgal, F.; Labrincha, J.A. Biotech Cementitious Materials: Some Aspects of an Innovative Approach for Concrete with Enhanced Durability. Constr. Build. Mater. 2013, 40, 1136–1141.
12. Jia, Z.; Deng, Z.; Li, L. Biomineralized Materials as Model Systems for Structural Composites: 3D Architecture. Adv. Mater. 2022, 34, 2106259.
13. du Plessis, A.; Broeckhoven, C.; Yadroitsava, I.; Yadroitsev, I.; Hands, C.H.; Kunju, R.; Bhate, D. Beautiful and Functional: A Review of Biomimetic Design in Additive Manufacturing. Addit. Manuf. 2019, 27, 408–427.
14. Sanga, R.; Kilumile, M.; Mohamed, F. Alternative Clay Bricks Inspired from Termite Mound Biomimicry. Case Stud. Constr. Mater. 2022, 16, e00977.
15. Hesse, P.R. A Chemical and Physical Study of the Soils of Termite Mounds in East Africa. J. Ecol. 1955, 43, 449–461.
16. Moskaleva, A.; Safonov, A.; Hernández-Montes, E. Fiber-Reinforced Polymers in Freeform Structures: A Review. Buildings 2021, 11, 481.

17. Körner, A.; Born, L.; Bucklin, O.; Suzuki, S.; Vasey, L.; Gresser, G.T.; Menges, A.; Knippers, J. Integrative Design and Fabrication Methodology for Bio-Inspired Folding Mechanisms for Architectural Applications. Comput. -Aided Des. 2021, 133, 102988. Comput. Aided Des. 2021, 133, 102988.
18. Körner, A.; Born, L.; Mader, A.; Sachse, R.; Saffarian, S.; Westermeier, A.S.; Poppinga, S.; Bischoff, M.; Gresser, G.T.; Milwich, M.; et al. Flectofold—A Biomimetic Compliant Shading Device for Complex Free Form Facades. Smart Mater. Struct. 2018, 27, 017001.
19. Gil Pérez, M.; Rongen, B.; Koslowski, V.; Knippers, J. Structural Design, Optimization and Detailing of the BUGA Fibre Pavilion. Int. J. Space Struct. 2020, 35, 147–159.
20. Allameh, S.M.; Miller, R.; Allameh, H. Mechanical properties of 3D printed biomimicked composites. In Proceedings of the Volume 12: Materials: Genetics to Structures; American Society of Mechanical Engineers: Pittsburgh, PA, USA, 2018; p. V012T11A001.
21. Liu, J.; Li, S.; Fox, K.; Tran, P. 3D Concrete Printing of Bioinspired Bouligand Structure: A Study on Impact Resistance. Addit. Manuf. 2022, 50, 102544.
22. Hershcovich, C.; van Hout, R.; Rinsky, V.; Laufer, M.; Grobman, Y.j. Thermal Performance of Sculptured Tiles for Building Envelopes. Build. Environ. 2021, 197, 107809.
23. Peeks, M.; Badarnah, L. Textured Building Façades: Utilizing Morphological Adaptations Found in Nature for Evaporative Cooling. Biomimetics 2021, 6, 24.
24. Sangiorgio, V.; Parisi, F.; Fieni, F.; Parisi, N. The New Boundaries of 3D-Printed Clay Bricks Design: Printability of Complex Internal Geometries. Sustainability 2022, 14, 598.
25. Dong, L.; Wang, Y.; Li, H.X.; Jiang, B.; Al-Hussein, M. Carbon Reduction Measures-Based LCA of Prefabricated Temporary Housing with Renewable Energy Systems. Sustainability 2018, 10, 718.
26. Adamu, M.; Alanazi, F.; Ibrahim, Y.E.; Alanazi, H.; Khed, V.C. A Comprehensive Review on Sustainable Natural Fiber in Cementitious Composites: The Date Palm Fiber Case. Sustainability 2022, 14, 6691.
27. Ibn-Elhaj, S.; Mounir, S.; Khabbazi, A.; Sarghini, H. Effect of Clay's Multilayer Composites Material on the Energy Efficiency of Buildings. J. Compos. Sci. 2022, 6, 151.
28. Institut d'Arquitectura Avançada de Catalunya CO-MIDA—Institute for Advanced Architecture of Catalonia. Available online: https://iaac.net/project/co-mida-en/ (accessed on 15 October 2022).
29. Thompson, D.; Augarde, C.; Osorio, J.P. A Review of Current Construction Guidelines to Inform the Design of Rammed Earth Houses in Seismically Active Zones. J. Build. Eng. 2022, 54, 104666.
30. Zaryoun, M.; Hosseini, M. Lightweight Fiber-Reinforced Clay as a Sustainable Material for Disaster Resilient Architecture of Future Buildings. Archit. Eng. Des. Manag. 2019, 15, 430–444.

31. Mu, B.; Zhang, A.; Wang, A. Biomimetic superhydrophobic cobalt blue/clay mineral hybrid pigments with self-cleaning property and different colors. In Springer Proceedings in Earth and Environmental Sciences; Springer: Berlin/Heidelberg, Germany, 2019; pp. 427–431.
32. Dong, J.; Zhang, J. Biomimetic Super Anti-Wetting Coatings from Natural Materials: Superamphiphobic Coatings Based on Nanoclays. Sci. Rep. 2018, 8, 12062.
33. De Andrade, T.A.B.; Beirão, J.N.D.C.; de Arruda, A.J.V.; Cruz, C. The Adaptive Power of Ammophila Arenaria: Biomimetic Study, Systematic Observation, Parametric Design and Experimental Tests with Bimetal. Polymers 2021, 13, 2554.
34. Charpentier, L.; Cruz, E.; Nenov, T.; Guidoux, K.; Ware, S. Pho'liage: Towards a kinetic biomimetic thermoregulating façade. In Bionics and Sustainable Design; Palombini, F.L., Muthu, S.S., Eds.; Environmental Footprints and Eco-Design of Products and Processes; Springer Nature: Singapore, 2022; pp. 367–401. ISBN 978-981-19181-2-4.
35. Cheng, Z.; Han, H.; Wang, F.; Yan, Y.; Shi, X.; Liang, H.; Zhang, X.; Shuai, Y. Efficient Radiative Cooling Coating with Biomimetic Human Skin Wrinkle Structure. Nano Energy 2021, 89, 106377.
36. Zhu, H.; Huang, Y.; Lou, X.; Xia, F. Beetle-Inspired Wettable Materials: From Fabrications to Applications. Mater. Today Nano 2019, 6, 100034.
37. Srivatsa, S.; Paćko, P.; Mishnaevsky, L.; Uhl, T.; Grabowski, K. Deformation of Bioinspired MXene-Based Polymer Composites with Brick and Mortar Structures: A Computational Analysis. Materials 2020, 13, 5189.
38. Evers, K.; Falco, S.; Grobert, N.; Todd, R.I. Nacre-like Alumina with Unique High Strain Rate Capabilities. J. Eur. Ceram. Soc. 2020, 40, 417–426.
39. Zhu, M.; Zhang, F.; Chen, X. Bioinspired Mechanically Interlocking Structures. Small Struct. 2020, 1, 2000045.
40. Kakisawa, H.; Sumitomo, T. The Toughening Mechanism of Nacre and Structural Materials Inspired by Nacre. Sci. Technol. Adv. Mater. 2011, 12, 064710.
41. Mirkhalaf, M.; Zhou, T.; Barthelat, F. Simultaneous Improvements of Strength and Toughness in Topologically Interlocked Ceramics. Proc. Natl. Acad. Sci. USA 2018, 115, 9128–9133.
42. Mostert, J.-P.; Kruger, J. Interlocking 3D printed concrete filaments through surface topology modifications for improved tensile bond strength. RILEM Bookseries; In Third RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2022; Springer: Cham, Switzerland, 2022; Volume 37, pp. 235–240.