Journal of Solar Energy Research (JSER)

Journal homepage: jser.ut.ac.ir

Improve thermal efficiency of the exterior shell of a building using natural non-woven composite materials

Mahbube Pakdel [a], Babak Alemi [b,*]

[a] *M.S. Student Architecture Technology, Architect and art Department, University of Kashan, Kashan, Iran.*
[b] *Assistant Professor, Architecture Faculty, Architect and art Department, University of Kashan, Kashan, Iran.*
Received: 2022-03-11
Accepted: 2022-06-30

Abstract

Silkworm cocoons are a natural biological and composite structure that has evolved over time and responds well to the environmental conditions for silkworms. Understanding the relationships of cocoon structure inspires the creation of materials such as low-weight, high-strength nonwoven bio composites. In this study, the descriptive-analytical method and logical reasoning, using sericin cocoon and natural fibers, which for various reasons such as lightness, non-pollution, and low-cost, can be a suitable alternative to artificial fibers, offer materials as a non-woven bio composite. These materials are suitable in terms of stability and energy consumption, can be used as thermal insulation. This performance is simulated for the hot and dry climate of Kashan city in the outer shell of the building and using the Honeybee energy analysis plugin in the Grasshopper environment. The results show that the proposed non-woven bio composite can help improve the thermal performance of the building by up to 12.7%.

Keywords: Bio mimicry; Silkworm cocoon; Bio composite with natural fibres; Bionic architectural

1. Introduction

The use of architectural composites in comparison with its widespread use in the marine and aerospace industries is in the early stages. This is largely due to the lack of general engineering standards for buildings or materials made of compo-site materials and the lack of attention of some architects to the use of new materials in design. In terms of stability, structures created with composite materials, to make proper performance, need fewer materials compared to similar structures, which leads to a simultaneous reduction in energy consumption and car-bon emissions during the production process. Advances in composite materials science offer new insights into their properties and applications in buildings. The biggest drawback of synthetic fibre-reinforced composites is the lack of solutions for their recycling except by burying or burning. [1] Research on environmentally friendly composites made from natural fibers is important due to the interest in environmentally friendly materials and concerns about re-source depletion, and non-woven composites are also part of these bio composites. Non-woven composites formed from fibres that were stacked without special order and texture and bonded together using adhesive (matrix) by chemical, mechanical or thermal methods. An example of this type of

*corresponding author :alemi@kashanu.ac.ir

composite in nature is the silkworm cocoon. Silk cocoon is a polymer composite of a single string of silk fibres with a length of about 1000-1500 meters, bonded by sericin and has porous microstructures with a specific hierarchy and in a multi-layered way. The fibre-forming protein called fibroin has a semi-crystalline structure and about 75% by weight of cocoon and sericin is an amorphous, water-soluble protein polymer that makes up 25% by weight. [2-3] each layer of silkworm cocoons has a different mechanical behavior and ultimately leads to the structure of irregular cocoons that have a good function against moisture, air flow, UV rays and impact and have a certain degree of heat retardant and are able to save heat. In view of the above, in this study, inspired by the unique two-component structure of the silkworm cocoon, it is suggested that the nonwoven bio composite production process consist of natural jute fibbers due to the abundance and low thermal conductivity and sericin (natural material and silk fibre binder in the cocoon). The pro-posed materials can have suitable functions in the building. These applications include structural reinforcement, waterproofing, light wall construction, floor and ceiling covering systems, partitioning and thermal insulation in the building shell and its use can help reduce energy consumption in the building. Its function as thermal insulation in the outer shell of the building in hot and dry climates is then analyzed by the Honeybee plug-in Grasshopper and the results of this simulation are evaluated.

Research questions:

1. How does the study of the structure and materials of silk cocoons and natural fibres lead to a non-woven composite model?

2. How does the proposed natural fibre nonwoven composite model help to improve performance in buildings?

2. Literature review

In the late 19th and early 20th centuries, materials scientists used advanced techniques such as SEM, DMTA, etc. to use silkworm cocoons as models for bio composites. In 2010, Chen studied the engineering aspects of cocoons as a bio-hybrid system by studying a wide range of types of cocoons and proposed a quantitative model that directly linked cocoon structure to its mechanical properties and could be applied to other composite. [4] In his 2010 study, Myer introduced the silkworm cocoon as a heterogeneous fibrous structure in diameter and density, and believed that the cocoon, despite its complex structure, maintained its moisture level and oxygen exchange with the outside environment. [5] In a study in 2019, the natural fiber non-woven composite model according to the structure of silkworm cocoons was made using jute and sericin natural fibres of silkworm cocoons and then, the effect of sericin binder content on the physical properties of nonwoven composite was tested. [6] Korjenic et al. Studied natural fibre bio composites as thermal insulation in combination with plant facades in construction, and considered the use of these materials to be environmentally friendly and effective in reducing energy and heat. [7] In their research, Khedari et al. Also propose a composite building using a wall-ceiling, consisting of natural fibres, cement and sand, which is very light and has a low conductivity. [8] Understanding bio composites and their properties can be a new path in architectural design, because building materials as a constructive element affect the shape and performance of buildings, especially in terms of stability and energy, and one of the most important issues studied in the sources that can provide the use of these materials in building, its structure is as a biological composite that is thermal and moisture insulating.

3. SILK COCOON

The silk cocoon has a layered structure, without texture and is made of two components of protein, sericin and silk fibres (fibroin). Sericin makes up one-fourth of the total weight of the cocoon, and its amount decreases from the outer layers to the inner layers, eventually leading to the formation of a highly interconnected network of fibres. The porous structure of the cocoon and its aerodynamic properties affect the air flow rate. The air velocity is much slower in the smaller cracks in the cocoon wall, and near the surface of the silk fibres, due to the adhesion of sericin. In addition, a number of airflow lines in the cocoon wall are terminated due to the loss of kinetic energy due to friction between the silk fibres and the air and air turbulence through the cocoon. Silkworm cocoons are resistant to temperature changes in the environment and temperature fluctuations inside the cocoon are low if the temperature in the environment changes. The silk cocoon provides a UV protective layer for the worm pupa, which sericin is responsible for absorbing. [9- 12]

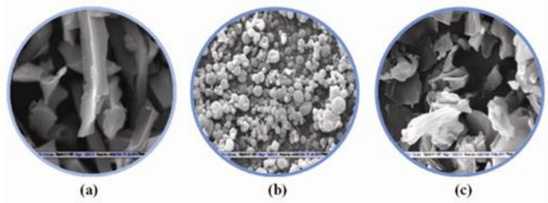


Figure 1. Schematic images of sericin samples (magnification × 5000x), from left to right: a) Standard sample, b) spray-dried sample, c) ice-dried simple. [3]

Sericin also has important biological properties such as corrosion resistance, antimicrobial activity, easy absorption of moisture, etc., and is known as a compatible and biodegradable substance .In the textile industry, sericin is a by-product of silk fiber production and is always looking for new applications of this protein in many research projects. Due to its amorphous nature, it dissolves easily in water at 60 ° C and returns to a gel state upon cooling, providing significant commercial, economic, and environmental benefits if recycled. [13- 15, 3]

4. NON-WOVEN NATURAL FIBER COMPOSITE MODEL

In this research, a model of a non-woven composite with natural fibres and a sericin cocoon binder is proposed, the structure of which will be described based on a leading process. The use of natural fibres is due to its good thermal properties and optimum strength, lightness, recyclability and easy access to it in many regions and countries. The use of these fibres has been used in the construction of building materials in the past and today, with increasing environ-mental concerns, it has been used in many studies in the preparation of bio composites. To identify and select natural fibres, it is necessary to first examine them based on their design needs and compare their strengths and weaknesses.

Table 1. Comparison of properties of natural fibers with each other as fibers used in non-woven fiber composite. [Authors]

Fibre	Density (gr/ cm^2)	Young modules (GPa)	Tensile strength (MPa)	Moisture absorption (%)	Elongation at break point (Longitudinal strain)	Termal conductivity (W/m-k) At a temperature of 23 ° C and a relative humidity of 50%	Medium thickness of fibers (μmm)
Jute [7,16,17]	1.3-1.4	26.5	400-800	93	1.5-1.8	0.0580	94.2
Flax [17,7]	1.5	27.6-46.9	300-1000	NA	2.7-3.2	0.0650	111.1
Hemp [18,7]	1.4	NA	550-900	13	NA*	0.0620	155.2
Sisal [16,17]	1.5	9.4-22	300-600	110	2-2.5	NA	NA
Coir [16]	1.1	3-6	95-100	8	47	NA	NA

* NA: not available

According to the table 1 and a comparison of the natural fibres mentioned in it, it can be seen that jute fibres usually resist rot and heat well and have a high tensile strength after flax and hemp fibres. Coir fibres have the lowest density and moisture absorption of all fibres and can float on water for a long time. All of these fibres are now used as fillers or reinforcements in composite materials and can be a suitable alternative to synthetic fibres. In this model, jute was considered as a natural fibre due to its lower thermal conductivity than hemp and flax and the abundance of these fibres and the ability to be cultivated in all regions, in the preparation of fibrous bio composite. After selecting the fibres, the material should be considered as a binder between the fibres, because in a natural fibrous composite with a porous structure without texture, the binder is between the fibres, which will lead to the formation of strength and strengthening of mechanical properties.

According to research, synthetic binders based on formaldehyde have important disadvantages such as water absorption, which can greatly reduce the life of the composite material, consume more energy due to the temperature of the process required for the polymerization of the synthetic binder. [19-21] In addition, formaldehyde-based chemical binders as toxic substances can cause side effects. [22] Based on this issue and the effect of sericin on silkworm cocoons as a natural binder, it can be used as a suitable alternative to synthetic binders in the production of natural fibre composites. In this study, sericin was considered as a binder between selected jute fibres for the production of non-woven bio composite materials. The amount of sericin, depending on the amount in the silkworm cocoon, can be used in the production of natural fibrous bio composites up to 30% by volume, and the rest should be made of natural fibres. The process of producing the proposed materials, which must be done in the workshop and is possible by prefabrication, begins with cutting the fibres into small lengths. The natural fibres are poured into a container and then sericin solution is added. The solution should then be stirred gently to achieve a homogeneous dispersion of the fibres in the solution. The prepared material is then poured into a metal mold according to the desired standard sizes. To remove moisture, create compaction between the fibres and produce the final product, the mixture must be placed inside a hot press machine and a composite panel must be produced under high pressure and temperature.

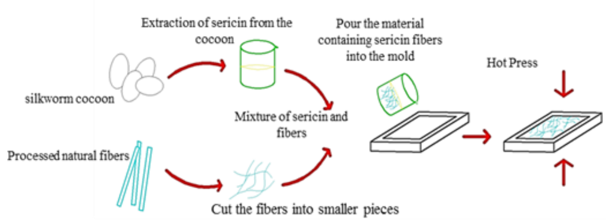


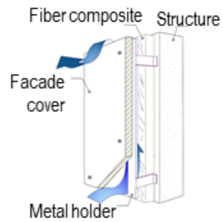
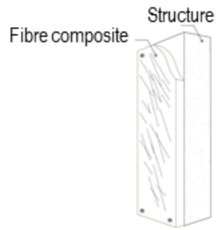
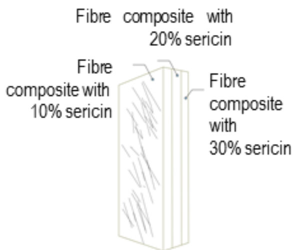
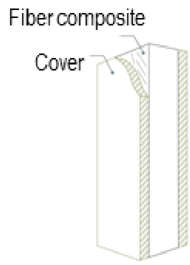
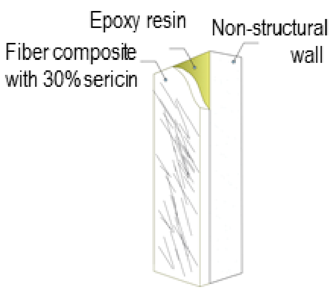
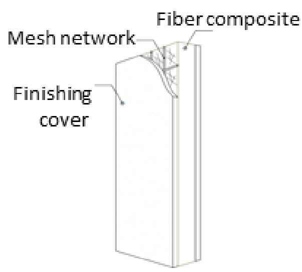
Figure 2. Production method of non-woven composite of natural fibres and sericin [Authors]

The production process of the proposed materials, which should be done in the manufactory and is possible by prefabrication, should be started by cutting jute fibers to a length of 1 cm. Pour the natural fibers into a container and then add the sericin solution. The solution should be stirred gently to achieve a homogeneous dispersion of fibers in the solution. Then the prepared material should be poured into a metal mold according to the desired standard sizes. To remove moisture, compress the fibers and produce the final product, the mixture must be placed inside a hot press machine and the composite panel must be produced under high pressure and temperature.

5. PROPOSED APPLICATIONS FOR NON-WOVEN COMPOSITE MATERIAL IN ARCHITECTURE

Low water absorption, maintaining resistance in humid environments, strength and load-bearing capacity, light weight, environment-friendly and non-environmental pollution, are among the advantages that can be mentioned for the non-woven composite of natural fibers. For this reason, it is considered that these new bionic materials will be suitable for use in building exterior shells, floor or ceiling systems, green roofs, partition wall, dropped ceiling, light and insulated walls in humid spaces, lightweight construction, ventilation systems and cooling systems.

Table 2. Investigating the advantages of using fiber non-woven composites and their proposed applications in architecture [Authors]

<table>
<tr><th colspan="4">Advantages of modern bionic materials (non-woven composite of natural fibers)</th></tr>
<tr><td>. Solve part of the function according to the type of application.
. No damage to the environment</td><td>. Economic (achieving a minimum in materials and energy).
. Flexibility and the possibility of prefabrication.</td><td>. Optimal physical strength
. Structural stylization
. Stability in humid environments</td><td>. Creating high performance
. Possibility of recycling
. Linking materials and structures</td></tr>
<tr><th colspan="4">Proposed applications of modern bionic material in architecture</th></tr>
<tr><td>1. Two-skin façade (As moisture and heat insulation)</td><td></td><td>2. Moisture enhancing coating of the structure</td><td></td></tr>
<tr><td>3. Production of layered fiber composite</td><td></td><td>4. New wood replacement materials - partitioning</td><td></td></tr>
<tr><td>5. Non-load-bearing wall reinforcement cover</td><td></td><td>6. Composite as a structure of light and insulated walls</td><td></td></tr>
</table>

In the "table 2", according to the proposed features for non-woven composite fiber materials, six proposed designs for their use in construction are given. One of the applications in these designs is the use of non-woven composite materials as thermal and moisture insulation in creating a double-skinned facade in the building. In the continuation of this research, by simulating this design, in the energy software, the thermal behavior of the proposed non-woven natural fiber composite is investigated.

6. Simulation of thermal behavior of nonwoven natural fibrous composite

To simulate the thermal behavior of jute-sericin nonwoven composite as a moisture and heat insulator, a shell view of the building was first presented in accordance with "table 2" and "figure 3". This layer is located as thermal insulation on the outside of the building wall and the outer wall of the building is assumed on the south side of the building. Architectural details of the building shell were selected to calculate the structure without bearing the load and reinforcing elements. To assign materials to the designed shell components of the building, 22 cm solid brick was considered for the exterior wall of the building and 3 cm plate brick was considered for covering the facade. The coefficient of thermal conductivity of brick materials is 0.9 and the coefficient of thermal conductivity of the air layer between bio composite thermal insulation and facade coating is 0.026, in accordance with the numbers given in Article 19 of the National Building Regulations. The thermal conductivity of jute non-woven bio composite as the proposed insulation materials was calculated approximately based on Maxwell's theoretical model (1) below and the proposed thickness was considered to be 5 cm.

$$K_c = \frac{K_m (K_f + 2K_m - 2V_f (K_m - K_f))}{K_f + 2K_m + V_f (K_m - K_f)} \qquad (1)$$

In this regard, V_F is the volume fraction of fiber. K_c, K_f and Km are the thermal conductivity of the composite, the fibers and the matrix, respectively. Based on the researches, it was observed that in measuring the thermal conductivity of fiber composite, the experimental results and the results of Maxwell's theoretical model in high fiber content with error rate of 4.8 are close to each other and the calculated and measured thermal conductivity of jute fiber composites Fiber is provided. [23]

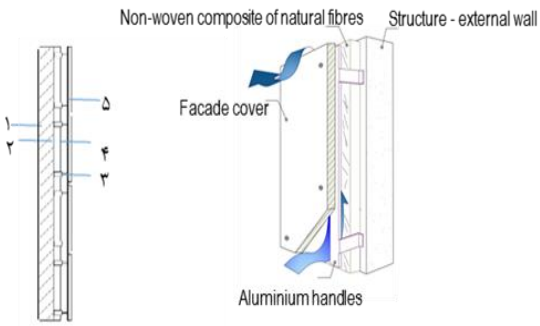


Figure 3. . Left) Cross section, 1. Internal wall of 22 cm solid brick, 2. Non-woven composite of natural fibers, 3. Aluminium handles, connecting the facade covering to the inner wall, 4. Air layer, 5. Facade covering.

The following table shows the specifications of the materials used in the design of the two-shell facade in the order of placement of the inner wall to the outer.

Table 3. Materials used in double-skinned facade design [Authors]

Layer from inner wall to outer wall	Materials	Thickness (cm)	Thermal conductivity* (W/m-k)
1	Brick	22	0.9
2	Bio composite jute-sericin	5	0.07
3	Aluminum (holder handle)	-	33.0
4	Air	5	0.026
5	Brick	3	0.9

* At a temperature of 23 ° C and a relative humidity of 50%

In this simulation, the hot and dry climatic conditions of Kashan city were considered.The climate of Kashan is hot for nine months of the year and cold only for three months of the year. For this reason, simulating and reviewing performance for the summer and warm months of the year is a priority. According to the statistics of Kashan meteorological station, August and July with an average temperature of 37 to 40 ° C are the warmest months of the year and January is the coldest month of the year with an average temperature of about -2 ° C .The average maximum temperature is 24.5 ° C and the average minimum temperature is 11 ° C .For this reason, the external temperature conditions of the building were considered in accordance with meteorological statistics and for its average temperature in the warm seasons of the year (+40) ° C. By determining the boundary conditions of indoor and outdoor environments, the hypothetical temperature inside 24 (equal to thermal comfort conditions) was determined.

Thermal simulation of the outer crust in Rhino and in the Grasshopper environment and its energy analysis was performed by the Honeybee plugin. Two modes were considered for the building shell. At first, the building shell was designed as a thermal insulator in the software environment without considering jute-sericin non-woven composite materials. In the second case, the proposed materials are placed in accordance with the architectural details of “figure 3” as insulation in the building shell and between the coverings materials of the facade and the building wall .Based on the output data of this simulation process, the amount of temperature difference in materials on the outside and inside of the building as well as the amount of heat transfer through surfaces in watts per square meter in Kelvin can be obtained. By comparing the two shell states of the building by considering the non-woven bio composite insulation of jute as thermal insulation between the inner and outer wall and without considering it, the performance of the proposed materials in reducing heat transfer in the building can be obtained.

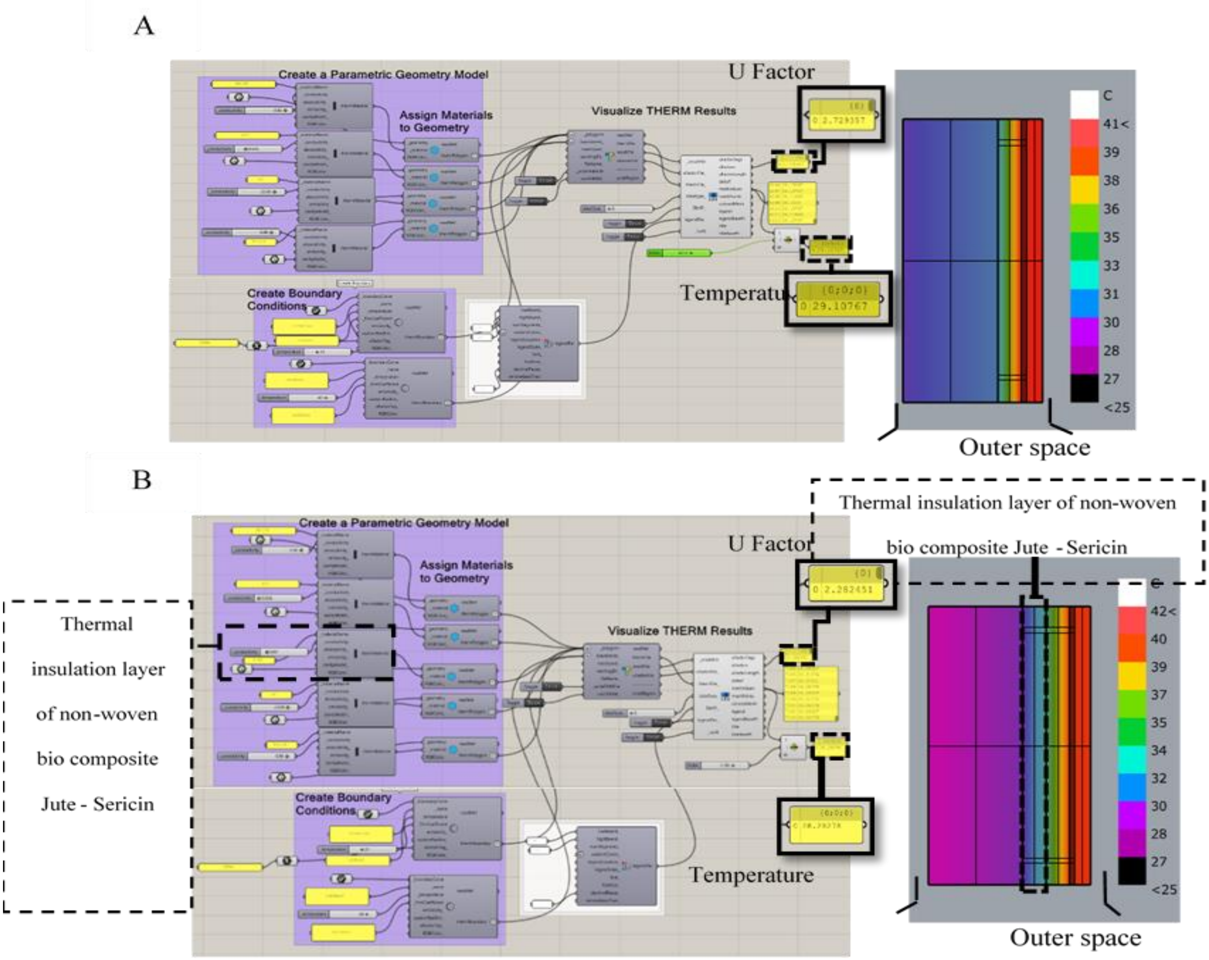


Figure 4. A) Simulation of the thermal behavior of the shell of the building without considering the thermal insulation layer of non-woven composite on the outside of the main wall of the building, left of the thermal analysis algorithm in Honeybee plugin in the hopper environment and right of the thermal analysis display, B) Simulation Thermal behavior of building shell facade by considering the layer of non-woven composite thermal insulation on the outside of the main wall of the building, the left side of the thermal analysis algorithm in the Honeybee plugin in the Grasshopper environment and the right side of the thermal analysis display. [Authors]

The amount of temperature difference inside and outside the building and heat transfer of the wall surface, in two modes of thermal simulation of the building shell, which was done in software, was obtained from the numerical outputs of the thermal analysis algorithm and can be seen in the table below.

Table 4. Investigation of numerical outputs from thermal simulation of building shell [Authors]

Building shell	Inner layer temperature (° C)	Outer layer temperature (° C)	Temperature difference between inside and outside layers (° C)	Heat transfer (w/ m^2. °K)
A*	29.2	38.6	2.72	9.4
B**	28.2	38.8	2.28	10.6
Percentage change of temperature difference between inside and outside layers (° C)				12.7%

* First case: Building shell - inner wall and exterior

**Second case: Building shell - inner wall and exterior and bio composite layer of jute-sericin as thermal insulation between them

As shown in “figure 4” and in the table above, the temperature difference between the outside and inside of the building will be greater when the non-woven composite insulation layer of natural jute-sericin fibers is placed between the facade shell and the building wall. This means that the proposed non-woven bio composite materials can be effective in improving the thermal performance up to 1.2 ° C and also by considering the numerical rate of heat transfer in watts from the wall surface per m^2, the value is 2.72 for the case of non-woven composite insulation with natural fibers. Jute and 2.28 w/ m^2. °K for the case where the shell has non-woven composite thermal insulation. Therefore, the presence of a thermal insulation layer of jute bio composite will help to increase the thermal efficiency up to 12.7% compared to when the building shell is considered without thermal insulation. According to the obtained thermal analysis and the study of numerical values in this analysis, the presence of non-woven composite with natural fibers as a thermal insulator in the outer shell has a good performance and reduces the penetration of heat into the building. Another point studied for the use of this bio composite material in the position of thermal insulation in the building, its comparison in terms of functionality with widely used mineral insulations such as fiberglass and mineral wool and expanded polystyrene thermal insulation.

Table 5. Comparison of thermal insulation materials in terms of thermal conductivity [Authors]

Material	Thermal conductivity* (W/m. °k)	Source
Expanded polystyrene	0.043	According to Article 19 of the National Building Regulations of Iran
Mineral wool	0.045	According to Article 19 of the National Building Regulations of Iran
Fiberglass	0.040	According to Article 19 of the National Building Regulations of Iran
Bio composite jute-sericin	0.067	Approximate calculation based on Maxwell relation (1)

*At a temperature of 23 ° C and a relative humidity of 50%

As shown in “table 5”, mineral wool and fiberglass have, on average, thermal conductivity of 0.045 and 0.040 (W / m. °Kelvin). These two materials are among the mineral materials that are used as thermal insulation in buildings due to their low conductivity. These materials have abnormal fibers and raw materials and will not be recyclable and reusable. The fibers used in fiberglass are harmful to human health and cause skin and lung diseases, and it is better to use less in the building. The average value of thermal conductivity in expanded polystyrene is 0.043 (W / m- °Kelvin) and with the application of thermal insulation in the building, it will have a good performance in reducing heat transfer. Disadvantages of expanded polystyrene insulation include flammability and the presence of unnatural and environmentally friendly raw materials. The coefficient of thermal conductivity of jute-sericin bio composite materials with approximate calculation based on Maxwell relation is equal to 0.067 .This value of thermal conductivity for fibrous bio composite material is slightly higher than the values of thermal conductivity coefficient of the three common thermal insulators mentioned above, and this indicates that jute sericin bio composite material as insulation has slightly weaker performance than other insulators. It will have the heat mentioned above. Instead, it is composed of completely natural and environmentally friendly materials, jute is a natural plant fiber and polymer that can be planted and harvested annually in hot and humid climates, including in Iran, and even in areas with low fertility that are no longer suitable for other crops. Cereals are not suitable, they can grow. In addition, jute can be easily grown without pesticides and chemical fertilizers. Jute fibers are completely biodegradable and are also known as golden fibers because of the aforementioned benefits. Since jute has universal consumption, high production potential and various uses, it has the second rank among plant fibers after flax. The binder of this bio composite, namely silicon sericin, is also completely natural, and the recycling and exploitation of sericin from the silkworm cocoon and fabric industry will bring economic and environmental benefits, because in the silk production process, a significant amount of sericin is separated from the silkworm cocoon. Discarded without use. Jute-Sericin nonwoven fiber bio composite is a lightweight material, resistant to moisture and heat, and has good strength against incoming loads. It is a component of green materials and is economically suitable for production and use. Non-woven bio composites due to their suitable mechanical and thermal behavior, can be used in various applications in construction. Further studies on these non-woven bio composites, due to their importance in materials science, conducting experiments related to them and their production, will be an important step in achieving environmental sustainability and reducing energy consumption.

7. Conclusion

By introducing suitable materials from renewable natural raw materials as natural fibers and using sericin silkworm cocoon, the production of non-woven bio composite was achieved, which is energy-friendly, environmentally friendly and economical, and has a good performance against heat and moisture loads. Shows itself. Considering the use of durable and light materials with suitable physical and mechanical properties in construction and architecture, it is more and more necessary today, to present a proposed model for the production of fiber non-woven composite panels that are governed by patterns and concepts in silkworm cocoon materials. It can be prefabricated, it will be very effective in building. One of the uses for these composites is thermal insulation, because the proper thermal performance of these materials, like today's mineral insulation, but with more desirable biological and economic benefits, and for this purpose, the thermal behavior of these new materials as thermal insulation of the building in the shell It was examined by energy analysis software and the results show that if we use this insulation between the exterior and the inner wall of the building, we will have up to 12.7% better performance than not using insulation in the facade shell, and this indicates appropriate behavior. Bio composite is a natural fiber introduced against moisture and heat transfer, and with this possibility, it can be used as one of the new building materials to meet the style and sustainability needs.

References

1. Bechthold, M. & Weaver, J. C, *Materials science and architecture. Nature Reviews Materials,* 2017, **2(12)**, p. 1-19.

2. Chen, F. Porter, D. Vallarta, F, *Silkworm cocoons inspire models for random fiber and particulate composites. The American Physical Society. Physical Review,* 2010, **4(82)**, p. 041911.

3. Gupta, D., Agrawal, A., & Rangi, *A, Extraction and characterization of silk sericin. Indian Journal of Fibre & Textile Research (IJFTR),* 2014, **4(39)**, p. 364-372,

4. Chen, F, *Silk cocoons as composites (Doctoral dissertation, Oxford University,* UK.3, 2011.

5. Blossman-Myer, B. & Burggren, W. W, *The silk cocoon of the silkworm, Bombyx mori: Macro structure and its influence on Tran's mural diffusion of oxygen and water vapor. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology,* 2010, **2(155)**, p.259-263.

6. Kwak, H. W., Eom, J., Cho, S. Y., Lee, M. E., & Jin, H. J, *High-toughness natural polymer nonwoven preforms inspired by silkworm cocoon structure. International journal of biological macromolecules,* 2019, **127**, p. 146-152.

7. Korjenic, A., Zach, J., & Hroudová, J, *The use of insulating materials based on natural fibers in combination with plant facades in building constructions. Energy and Buildings,* 2016, **116**, p. 45-58.

8. Khedari, J., Suttisonk, B., Pratinthong, N., & Hirunlabh, J. *New lightweight composite construction materials with low thermal conductivity. Cement and Concrete Composites,* 2001, **23(1)**, p. 65-70.

9. Jin, X., Zhang, J., GAO, W., Li, J., & Wang, X. *Interfacial heat transfer through a natural protective fibrous architecture: a wild silkworm cocoon wall. Textile research journal,* 2015, **85(10)**, p. 1035-1044.

10. Zhang, J, Li, J, Jin, X, Du, S, Kaur, J, & Wang, X, *Natural and highly protective composite structures–wild silkworm cocoons. Composites Communications*, 2017, **4**, p.1-4.

11. Chen, F., Porter, D., & Vollrath, F, *Silk cocoon (Bombyx mori): multi-layer structure and mechanical properties. Acta Biomaterialia*, 2012, **8(7)**, p. 2620-2627.

12. De Lima, A. G. B., Neto, S. F., & Silva, W. P, *Heat and mass transfer in porous materials with complex geometry: fundamentals and applications. In Heat and mass transfer in porous media, Springer, Berlin, Heidelberg,* 2012, p. 161-185.

13. Martínez, D. C. C., Zuluaga, C. L., Restrepo-Osorio, A., & Álvarez-López, C, *Characterization of sericin obtained from cocoons and silk yarns. Procedia engineering,* 2017, **200**, p. 377-383,

14. Mondal, M., Trivedy, K., & NIRMAL, K. S, *The silk proteins, sericin and fibroin in silkworm, Bombyx mori Linn,-a review*.2007.

15. Padamwar, M. N., & Pawar, A. P, *Silk sericin and its applications: A review*, 2004.

16. Sen, T., & Reddy, H. J, *Application of sisal, bamboo, coir and jute natural composites in structural upgradation. International Journal of Innovation, Management and Technology*, 2011 **2(3)**, p.186.

17. Gon, D., Das, K., Paul, P., & Maity, S, *Jute composites as wood substitute. International Journal of Textile Science*, 2012, **6(1)**, p. 84-93

18. Domke, P. V., & Mude, V. D, *Natural fiber reinforced building materials. IOSR J. Mech.* Civ. Eng, 2015, **12**, p. 104-107.

19. Rwawiire, S., Tomkova, B., Militky, J., Hes, L., & Kale, B. M, *Acoustic and thermal properties of a cellulose nonwoven natural fabric (barkcloth). Applied acoustics*, 2017, **116**, p.177-183,

20. Nakanishi, E. Y., Cabral, M. R., de Souza Gonçalves, P., dos Santos, V., & Junior, H. S, *Formaldehyde-free particleboards using natural latex as the polymeric binder. Journal of Cleaner Production*, 2018, **195**, p.1259-1269.

21. Silva, D. A. L., Lahr, F. A. R., Varanda, L. D., Christoforo, A. L., & Ometto, A. R, *Environmental performance assessment of the melamine-urea-formaldehyde (MUF) re-sin manufacture: a case study in Brazil. Journal of Cleaner Production*, 2015, **96**, p.299-307,

22. Salthammer, T., Mentese, S., & Marutzky, R, *Formaldehyde in the indoor environment. Chemical reviews,* 2010, **4(110)**, p.2536-2572.

23. Pujari, S., Ramakrishna, A., & Padal, K. T. B, *Investigations on thermal conductivities of jute and banana fiber reinforced epoxy composites. Journal of the Institution of Engineers (India): Series D,* 2017, **1(98)**, p.79-83.