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Optimum Details of Thermal-Meta Structures for Enhancing the Insulation Capacity of Concrete Panels

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Abstract - This study examined the flexural strength and thermal transfer resistance of thermal-meta structures developed for enhancing the insulation capacity of concrete walls and panels. The thermal-meta structure consisted of a paper honeycomb, laminated to be waterproof and incombustible with infilling materials. Lateral deformation of thermal-meta structures was analyzed from the finite element analysis under the simulation of concrete lateral pressure calculated for walls to determine the thickness, size, and height of the honeycomb cells. The effect of different infilling materials, such as air, EPS bead, urethane foam, paraffin, mixture of paraffin and aerogel, on the thermal transfer resistance of thermal-meta structures was also examined from thermal conductivity tests conducted in accordance with KS F 9016. Considering the structural safety against concrete lateral pressure and better thermal resistance, the details of a thermal-meta structure indicated the thickness, size, and height of the honeycomb cells was 4.5 mm, 50 mm, and 70 mm, respectively. The laminate thickness attached on both sides of the honeycomb was 0.8 mm; and no infilling materials were required for the honeycomb cells to form the closed-pore system

***Keywords*:** Thermal-meta Structures, Honeycomb cells, Laminate, Thermal Conductivity, Insulation, Concrete Lateral Pressure

1. Introduction

In order to achieve greenhouse gas reduction goals, the government is gradually strengthening standards related to energy reduction that directly affect the cooling and heating load of buildings (Park et al.,2016). Among policies related to energy conservation, the standards for thermal transmittance of exterior walls of buildings are being strengthened depending on the region and part of the building. This enhancement of thermal conductivity performance causes the thickness of the insulation material to gradually increase. Yoo et al. (2019) showed that the thickness of the wall, including insulation, can increase to more than 800 mm to satisfy the thermal transmittance of 0.15 W/m2·K.

This enhancement of thermal conductivity performance is causing the thickness of the external finishing material to gradually increase. Yoo et al. (2019) showed that the thickness of the wall including insulation can increase to more than 800 mm in order to satisfy the thermal transmittance of 0.15 W/m2·K. In other words, considering the strengthened thermal transmittance standards, the importance of insulation materials in houses is increasing further.Expanded polystyrene (EPS), which is most commonly used as an insulating material, has a low heat transfer capacity with a thermal conductivity of about 0.043 W/m·K, but has environmental hazards, structural vulnerability, and flame retardant performance of up to grade 2 (semi-non-combustible grade). There is a problem of vulnerability to fire (Kim, 2019). Previous researchers (Lee et al., 2019; Lee et al., 2003) conducted research on lowering the density of materials as a way to reduce the heat transmittance of concrete panel finishing materials that can replace EPS and satisfy non-combustible ratings. Lee et al. (2019) confirmed that in lightweight concrete using bottom ash aggregate and air bubbles, when the air bubble mixing rate is 15%, the thermal conductivity value is about 20% lower than that of general lightweight aggregate concrete. Lee et al. (2003) showed that thermal conductivity decreased by an average of 12% in lightweight concrete with EPS beads added. However, in these studies, the panel thickness required to satisfy the thermal transmittance of 0.15 W/m2·K is still at a thick level of approximately 600 mm.

In general, there are limits to satisfying the heat transmittance standards required by the government by using inorganic materials as fire retardants. Accordingly, in this study, as a way to overcome this problem, the idea of inserting a thermal meta structure in the center of the concrete panel was devised. The structure has a structure that reduces heat transfer power by arranging thermal meters with low thermal conductivity in a network or plate shape. In particular, thermal metastructures have significantly different heat transfer efficiencies depending on the materials used (Hong et al., 2018). Yoon et al. (2018) confirmed the applicability of thermometers for the purpose of reducing temperature changes in specific areas. Their field of application focuses only on mechanical materials, so research on replacing insulation materials has not been expanded. Therefore, in order to use it as a concrete panel insulation using a thermal meta structure, safety and thermal conductivity against the pouring side pressure of the concrete must be confirmed when inserted inside.

This study presents the optimal detailing of embedded thermal-meta structures to reduce the thermal conductivity of concrete panels. The shell size (Tv) and thickness (Tw) of the thermal-meta structure were determined considering the resistance to concrete lateral pressure and thermal conductivity from finite element analysis. The determined details were confirmed to be safe against the lateral pressure of concrete placement due to the attachment of the plate through a bending test. Finally, the thermal-meta structure was inserted into the insulating concrete and the thermal conductivity was evaluated according to the internal filling material.

2. Thermal-meta structure

2.1. Principles and components of thermal-meta structure

Thermal -meta structure is an insulating layer with a repetitive pattern and functions to artificially block heat (Seo et al., 2018; Cha et al., 2019). In particular, thermal-meta structures are effective in blocking heat transfer by forming a sealed space inside the structure, and the efficiency of heat blocking can be improved by adjusting the size, periodicity, and arrangement of the space (Yoon et al., 2018) . Taking this characteristic into consideration, a honeycomb structure was applied inside the thermal -meter, which creates a space to contain materials with low thermal conductivity. As shown in Figure 2, the thermal-meta structure is composed of a thermal meta, which is a core material, and a plate attached to both sides of the thermal-meta, and the inside is filled with a material with low thermal conductivity.

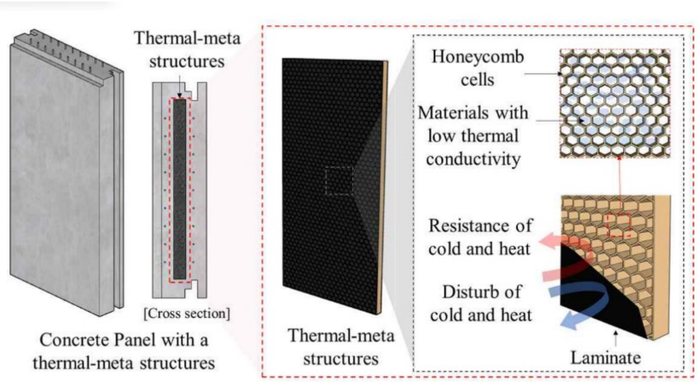
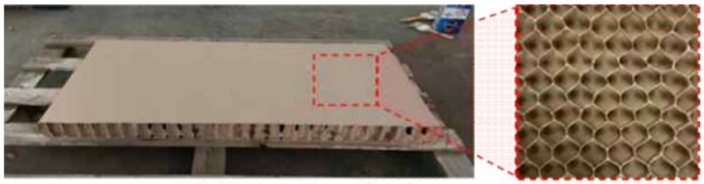
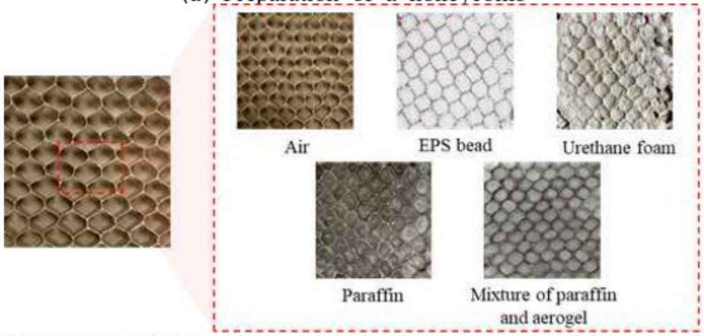


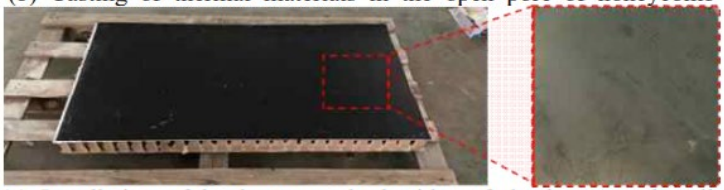
Fig. 1: Concept of the developed thermal-meta structures.



(a) Preparation of a honeycomb



(b) Casting of thermal materials in the open pore of honeycomb



(c) Installation of laminates on both sides of the honeycomb cells

Fig. 2: Production of the thermal-meta structures

2.1. Material properties

Thermal meta structure used materials that can prevent deformation from moisture and the lateral pressure of concrete placement. The honeycomb is commonly sold on the market and was chosen as a paper honeycomb with low density (0.18 g/cm3) and thermal conductivity (0.1 W/m·K). The plate material used was a laminate with waterproof and moisture-proof properties. The honeycomb and laminate were commercially available kraft honeycomb board and high-pressure laminate (HPL). Their thickness is 70 mm and 0.8 mm respectively, which are the most used thicknesses. The physical properties of honeycomb and laminate are shown in Table 1.

Table 1: Physical properties of materials used for the thermal-meta structures

Material	Thermal conductivity (W/m·K)	Specific heat (J/g·K)	Density (g/cm3)
Honeycomb	0.1	1.22	0.18
Laminate	0.3	1.44	0.9~1.0

Their thermal conductivities are 0.1 W/m·K and 0.3 W/m·K, respectively. The specific heat of honeycomb is 1.22 J/g·K. The inside of the honeycomb is composed of a shell and a core and has a hexagonal honeycomb shape, making it an efficient structure to resist external forces. Laminate is composed of several layers impregnated with heat-resistant synthetic resin at high temperature and pressure. The main components are kraft paper impregnated with phenolic resin, decorative board impregnated with thermoplastic resin or thermosetting resin sheet, and transparent protective paper. These laminates have semi-non-flammable properties. The density and specific heat of the laminate are 0.9 to 1.0 g/cm3 and 1.44 J/g·K, respectively. The mechanical properties of the honeycomb and laminate of the thermal meta structure are shown in Table The elastic modulus (E), Poisson's ratio (ν), and compressive strength (f_c) of the honeycomb are 142 MPa and 0.40.25 respectively, and in the laminate, these values are 9,000 MPa, 0.3, and 20 MPa, respectively. Table 3 shows the cross-sectional sizes of the honeycomb and laminate applied in each analysis and experiment. The inside of the honeycomb was filled with materials with low thermal conductivity such as air, EPS beads, urethane foam, paraffin, and a mixture of paraffin and airgel. Their physical properties are shown in Table 4. The thermal conductivity of EPS beads, urethane foam, and airgel is 0.03 to 0.035 W/m·K, which is similar to that of EPS. The thermal conductivity of paraffin was 0.35 W/m·K, the highest value among the compared materials, while the thermal conductivity of air was the lowest at 0.024 W/m·K. The mixture of paraffin and airgel was mixed in a 1:1 ratio.

Table 2: Mechanical properties of materials used for the thermal-meta structures

	E (MPa)	ν	f_c(MPa)
Honeycomb	142	0.4	0.25
Laminate	9000	0.3	20

Table 3：Size of cross section applied to analysis and experiment

	Honeycomb			Laminate
	Height (mm)	Thickness of the shell (mm)	Size of the shell (mm)	Thickness (mm)
Finite element analysi	70	4.5	50	0.8
Thermal conductivity	20	4.5	50	0.8
Flexural test	70	4.5	50	0.8

Table 4: Physical properties of infilling materials

Meterial	Air	EPS bead	Urethane foam	Paraffin	Aerogel
Thermal conductivity (W/m·K)	0.024	0.035	0.034	0.35	0.03
Density (kg/m3)	1.18@ 20℃	35	33	777	25
Specific heat (J/(kg·K))	1007	2300	1400	485	900

3. Finite element analysis

3.1. Analysis procedure

For finite element analysis, Abacus (DS Simulia Corp, 2016), a general-purpose analysis program, was used. Figure 3 shows a conceptual diagram of the analysis model for the thermal meta structure. The honeycomb and laminate that make up the thermal meta structure have shell elements with 6 degrees of freedom at the nodes and 8 square nodes that enable more precise numerical analysis of bending. It was modeled with S8R.

The honeycomb and the laminate were simulated to merge and behave as one. The constitutive equations of these materials were assumed to be fully plastic materials with isotropy according to the Von-mises fracture criterion. As shown shown in Figure 4, the boundary condition of simple support was set on the bottom of the thermal meta structure, and uniformly distributed loads were applied to both sides to simulate concrete lateral pressure. The load was calculated using using the following equation according to the standards of the Concrete Standard Specification (Korea Standard Specification 2022).

$$\mathrm{P} = \mathrm{WH} \tag{1}$$

Here, P, W, and H represent the lateral pressure of concrete (kN/m2), the unit weight of raw concrete (kN/m3), and the pouring height of concrete (m), respectively. W and H for analysis were assumed to be 14 kN/m3 and 0.228 m, respectively. Using the calculated lateral pressure (0.00319 MPa) as the maximum value, the numerical analysis used an implicit method based on direct solution, and geometric nonlinearity was considered to take into account lateral and buckling deformations that may occur in the laminate.

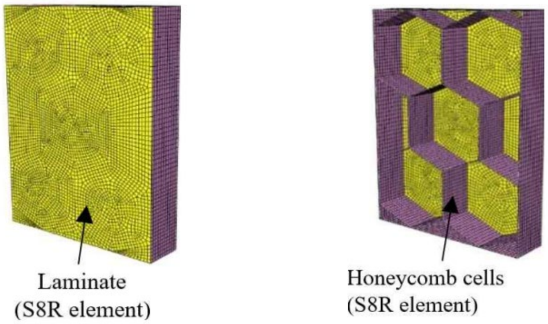


Fig. 3: Conceptual modeling diagram of finite element analysis model

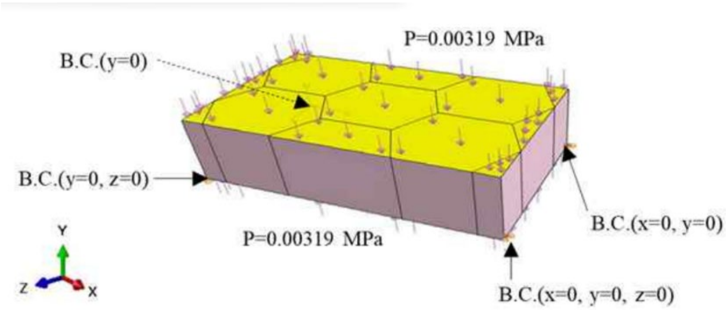
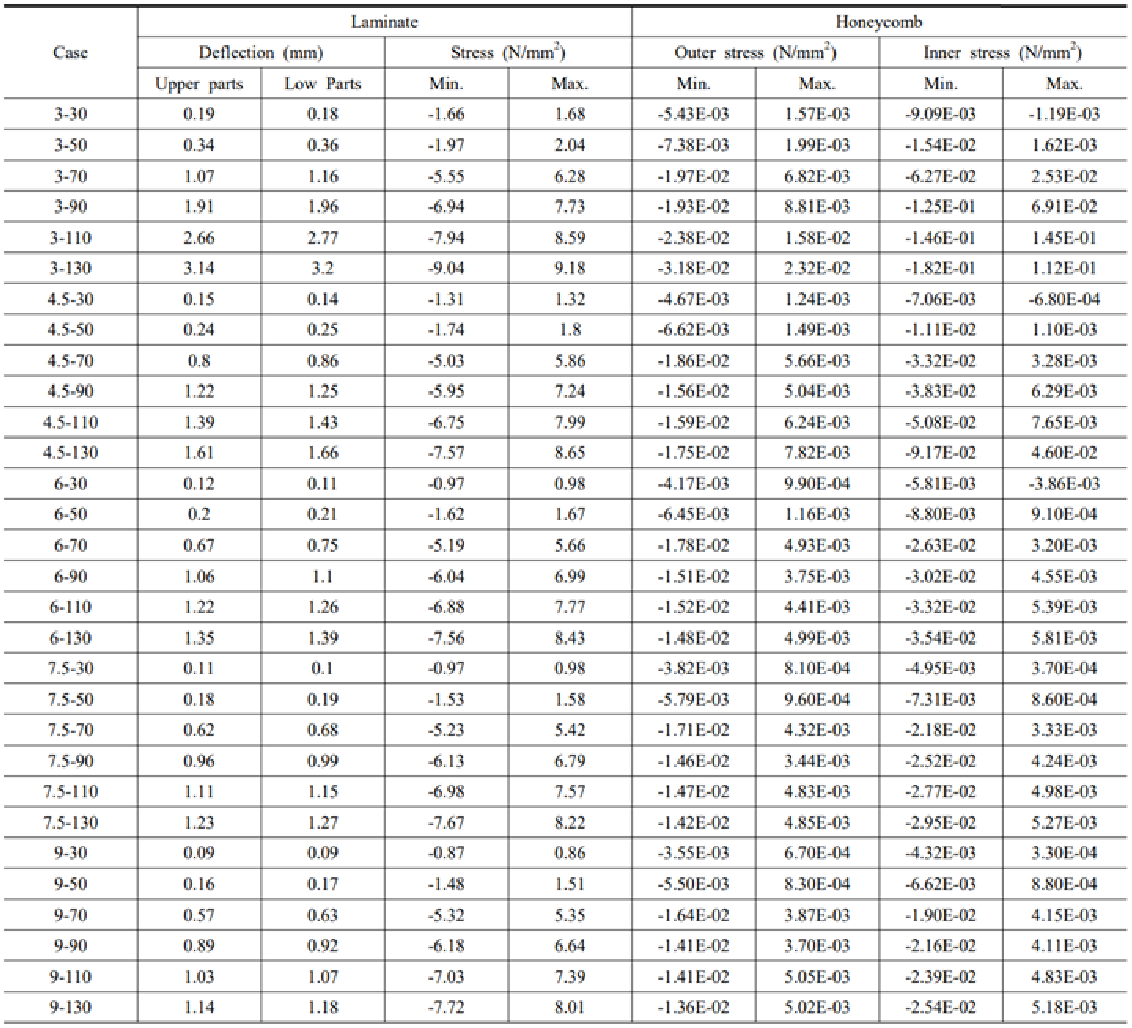


Fig. 4: Details of applied loads and boundary conditions in the FEM analysis

3.2. Analysis result

The analysis results of the thermal meta structure are shown in Table 5. As a result of the analysis, the stresses on the outside of the honeycomb and the laminate were the highest at 0.0232 N/mm2 and 9.18 N/mm2 in the 3-130 model. At this time, the maximum deflection of the laminate was 3.2 mm. The stress of honeycomb and laminate introduced by pouring lateral pressure increased as T_w became smaller or T_v became larger. In particular, the effect of changes in T_v was significant. The stresses of honeycomb and laminate increased by about 1.8 times when T_v increased by 1.4 times.

This is because an increase in Tv significantly reduces the area that can resist external forces. In addition, it was confirmed that in the honeycomb, when Tw is 3 mm and Tv is more than 70 mm, significant lateral deformation occurs reaching the target load. On the other hand, it was confirmed that no lateral deformation occurred in honeycombs with of 6 mm or more or Tv of 50 mm or less. The laminate did not experience lateral deformation regardless of Tw and Tv.



Case	Laminate				Honeycomb			
	Deflection (mm)		Stress (N/mm²)		Outer stress (N/mm²)		Inner stress (N/mm²)	
	Upper parts	Low Parts	Min.	Max.	Min.	Max.	Min.	Max.
3-30	0.19	0.18	-1.66	1.68	-5.43E-03	1.57E-03	-9.09E-03	-1.19E-03
3-50	0.34	0.36	-1.97	2.04	-7.38E-03	1.99E-03	-1.54E-02	1.62E-03
3-70	1.07	1.16	-5.55	6.28	-1.97E-02	6.82E-03	-6.27E-02	2.53E-02
3-90	1.91	1.96	-6.94	7.73	-1.93E-02	8.81E-03	-1.25E-01	6.91E-02
3-110	2.66	2.77	-7.94	8.59	-2.38E-02	1.58E-02	-1.46E-01	1.45E-01
3-130	3.14	3.2	-9.04	9.18	-3.18E-02	2.32E-02	-1.82E-01	1.12E-01
4.5-30	0.15	0.14	-1.31	1.32	-4.67E-03	1.24E-03	-7.06E-03	-6.80E-04
4.5-50	0.24	0.25	-1.74	1.8	-6.62E-03	1.49E-03	-1.11E-02	1.10E-03
4.5-70	0.8	0.86	-5.03	5.86	-1.86E-02	5.66E-03	-3.32E-02	3.28E-03
4.5-90	1.22	1.25	-5.95	7.24	-1.56E-02	5.04E-03	-3.83E-02	6.29E-03
4.5-110	1.39	1.43	-6.75	7.99	-1.59E-02	6.24E-03	-5.08E-02	7.65E-03
4.5-130	1.61	1.66	-7.57	8.65	-1.75E-02	7.82E-03	-9.17E-02	4.60E-02
6-30	0.12	0.11	-0.97	0.98	-4.17E-03	9.90E-04	-5.81E-03	-3.86E-03
6-50	0.2	0.21	-1.62	1.67	-6.45E-03	1.16E-03	-8.80E-03	9.10E-04
6-70	0.67	0.75	-5.19	5.66	-1.78E-02	4.93E-03	-2.63E-02	3.20E-03
6-90	1.06	1.1	-6.04	6.99	-1.51E-02	3.75E-03	-3.02E-02	4.55E-03
6-110	1.22	1.26	-6.88	7.77	-1.52E-02	4.41E-03	-3.32E-02	5.39E-03
6-130	1.35	1.39	-7.56	8.43	-1.48E-02	4.99E-03	-3.54E-02	5.81E-03
7.5-30	0.11	0.1	-0.97	0.98	-3.82E-03	8.10E-04	-4.95E-03	3.70E-04
7.5-50	0.18	0.19	-1.53	1.58	-5.79E-03	9.60E-04	-7.31E-03	8.60E-04
7.5-70	0.62	0.68	-5.23	5.42	-1.71E-02	4.32E-03	-2.18E-02	3.33E-03
7.5-90	0.96	0.99	-6.13	6.79	-1.46E-02	3.44E-03	-2.52E-02	4.24E-03
7.5-110	1.11	1.15	-6.98	7.57	-1.47E-02	4.83E-03	-2.77E-02	4.98E-03
7.5-130	1.23	1.27	-7.67	8.22	-1.42E-02	4.85E-03	-2.95E-02	5.27E-03
9-30	0.09	0.09	-0.87	0.86	-3.55E-03	6.70E-04	-4.32E-03	3.30E-04
9-50	0.16	0.17	-1.48	1.51	-5.50E-03	8.30E-04	-6.62E-03	8.80E-04
9-70	0.57	0.63	-5.32	5.35	-1.64E-02	3.87E-03	-1.90E-02	4.15E-03
9-90	0.89	0.92	-6.18	6.64	-1.41E-02	3.70E-03	-2.16E-02	4.11E-03
9-110	1.03	1.07	-7.03	7.39	-1.41E-02	5.05E-03	-2.39E-02	4.83E-03
9-130	1.14	1.18	-7.72	8.01	-1.36E-02	5.02E-03	-2.54E-02	5.18E-03

Table. 5: Analytical results on the structural performance of the developed thermal-meta structures.

4. Detailed presentation of optimal thermal meta structure

Figure 5 shows the cross-sectional details of the thermal metastructure determined based on the analysis in Chapter 3. The thermal meta structure is composed of paper honeycomb and laminate on both sides. The thickness of the laminate is 0.8 mm. The height of the honeycomb is 70 mm, and the inner shell thickness (Tw) and size (Tv) are 4.5 mm and 50 mm, respectively. The filling material for the closed space inside the honeycomb is air. A thermal metastructure with these details has a low thermal conductivity of 0.05 W/m·K and can resist lateral pressure when placing insulating concrete.

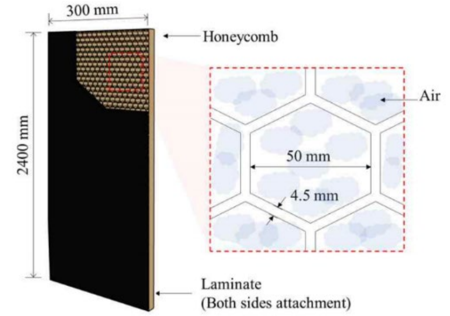


Fig. 5: Optimum details of the developed thermal-meta structure

4. Conclusion

To improve the thermal resistance of concrete panels and walls, a thermal-meta structure that can be used as a core material in these members was presented.

1) In the finite element analysis, the honeycomb did not deform due to concrete lateral pressure when the shell thickness (T_W) was more than 6 mm or the shell size (T_V) was less than 50 mm.

2) The thermal conductivity of the thermal meta-structure using air as an internal filling material was 0.05 W/m·K, which was about 30% of that of the thermal meta-structure using paraffin. Additionally, this is approximately 1.16 times the thermal conductivity of commonly used EPS, which is similar.

3) In order to apply a thermal meta structure to a concrete panel, a detailed review of the reinforcement reinforcement and cross-section thickness is required.

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