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Investigating the Effects of Bacteria and Heat on the Compressive Strength of Lightweight Concrete

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Abstracts

Nowadays, the use of light weight and yet resistant materials has a special place in the construction industry. Lightweight concrete is one of the materials that have been widely used in the construction industry due to its light weight, easier transportation and reduced production costs. Recently, the huge and extensive developments in concrete technology have been able to make significant progress in the concrete production industry by using new methods. The use of bacteria is considered a new and effective strategy in the concrete manufacturing industry. In this study, the role of calcite deposits on the compressive strength of lightweight concrete is investigated, before and after heat treatment of 150, 300, 450, 600 degrees celsius. The results obtained after examining the samples that were processed for 28 days in water and water containing calcium chloride and urea showed that the compressive strength of all samples decreased after being exposed to saturated heat. In addition, the presence of bacteria in the samples before the application of heat caused an increase. There is a significant increase in the compressive strength, and after the application of heat, the compressive strength of samples containing bacteria has a lower decreasing trend than the samples without bacteria, which indicates the positive effect of bacteria on the compressive strength of concrete even after applying heat.

Keywords: Lightweight concrete • Bacteria • Heat • Calcite precipitates • Compressive strength

Introduction

The production of construction materials with a high quality to be utilized in the building of resistant and sustainable structures is nowadays of great importance. Paying attention to the fast evolution in the construction industry in recent decades has led to the utilization of lightweight concrete as one of the most widely used materials in the building industry. In comparison to normal concrete, some characteristics of this concrete type include light weight, easier transportation, lower production costs, reduction of building's dead loads, and improvement of sustainability, thermal insulation, and high strength against heat [1-4]. It can generally be stated that the concrete's ability and high tolerance against heat are due to its low thermal conductivity and specific heat. The existence of these two characteristics of lightweight concrete is an undeniable fact. Despite the specific strength of concrete against heat, some variations can still be observed in the physical and mechanical properties of concrete including, variations in the compressive and tensile strength, elasticity modulus, color, and the appearance of concrete after being subjected to high temperatures [5-8]. Thus, a proper investigation of concrete's behavior subjected to heat can provide a good opportunity to conduct many research works.

The performed investigations of the cement matrix show the firm and dense structure of the C-S-H gel. The formation of dense gel produced through the reaction of cement and water is observable after the hydration process, as these nanostructures can be observed as weak fiber crystals at the beginning of the formation process [9]. The existence of this dense gel in the concrete's structure is an important factor in increasing the compressive strength of concrete. The obtained results from the studies of Hertz indicate that the decomposition process of the C-S-H gel starts at 600°C, and at 800°C, the structured gel deteriorate, which finally melts at 1150°C [10]. This process can be recognized as one of the important factors in weakening the concrete's strength at high temperatures. In other words, after being subjected to high temperatures, the main structure of concrete is weakened due to the release of physical and chemical water inside the concrete, which can lead to significant changes in the mechanical properties of concrete, including a sharp reduction in the compressive strength. The obtained results from the studies of Bastami et al. confirm this conclusion, as after heating to 800°C, a decrease of 80% was reported in the compressive strength of concrete [11]. With the evaporation and release of the water inside the concrete and finally the weakening of the intermolecular forces of the particles, cracking in the inner and surficial parts and also the

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disintegration of concrete can be expected. Researchers stated that adding fibers to concrete can prevent the risks of concrete's disintegration at high temperatures [12-14]. Also, the results of past studies show that fibers used inside the concrete structure can limit the expansion of the occurred cracks in concrete to an acceptable level [15]. Concrete is generally considered a brittle material in modern fracture mechanics that decreases compressive and tensile strength. Thus, it can be stated that using fibers plays an important role in limiting these fractures, enhancing the tensile and flexural strength, and improving the characteristics and durability of concrete [16-22]. Fibers used in concrete are mainly classified as artificial fibers, made and produced merely from chemical compounds. Therefore, they do not possess a cellulosic or proteinic structure, and nature does not play a role in their production. Thus, they can be considered environmentally harmful materials. This study attempted to employ more novel methods as far as possible that are regarded as environmentally friendly to improve the physical and mechanical properties of concrete subjected to high temperatures instead of using chemical and traditional techniques. To that aim, utilizing bacteria is one of these novel methods [23].

Some bacteria that precipitate calcite inside the damaged parts of concrete can result in the remediation of cracks at the concrete's surface. Moreover, biological carbonate can play a major role in decreasing water absorption by reducing the porosity existing in the concrete environment [24]. The researchers found that the biological activities of bacteria that lead to the formation of calcium carbonate deposits can improve the mechanical parameters of concrete, including its compressive strength. [25-28]. Bacteria that are able to form calcium carbonate deposits mainly use urea as an energy source in environments enriched with calcium chloride and urea (Figure 1). During the activity of bacterial urease, which will eventually lead to the formation of calcium carbonate deposits, it starts with the hydrolysis of urea [29,30]. The pH of the environment is an important factor in this process that is effective in urea hydrolysis. The occurred reactions during the urea hydrolysis can be considered a triggering factor, which leads to an increase in the pH of the environment. An increase in the pH can decline the bacterial activities besides some negative effects on the concrete [31]. The bacteria *Sporosarcina pasteurii* was employed in this study, a soil living, non-pathogenic strain, which does not threaten human health.

The test results show that 9.3 is a suitable pH for the optimum activity and better precipitation of the *Sporosarcina pasteurii* strain [32]. Besides the effects that mineral producing bacteria have on the mechanical components of concrete, their impact on the rehabilitation of lime structures, wastewater treatment (chemicals), reducing soil pollution, enhancing the strength of gravel and sand, and reducing greenhouse gas effects are observable. The present study aims to investigate the performance of a microorganism strain from the bacillus group, namely *Sporosarcina pasteurii*, on the compressive strength of lightweight concrete before and after heat application. To that aim, specimens were separately cured in two different media, including water and water containing urea and calcium chloride, for 28 days. In this research, the influence of air-entraining admixtures on the specimens was also examined.

Materials and Methods

Bacteria

A urease-producing microorganism, namely *Sporosarcina pasteurii*, was employed in this research. The mentioned strain (PTCC1645-DSM 33) was purchased as a lyophilized form from Persian Type Culture Collection (PTCC). After the culturing stages, the microorganism was cultured at a concentration of 106 cells/ml in its specific culture medium presented in Table 1. Then it was incubated at 28°C, 200 rpm for 48 hours. After the incubation time, the grown bacteria and their medium culture were taken out from the incubator to be added to the water considered for the mix design (Figure 1).

Compounds	urea	Distilled water	agar	Meat extract	Peptone
Amount	20 g	1 lit	15 g	3 g	5 g

Table 1. Culture medium of *Sporsarsina pastori* bacteria.

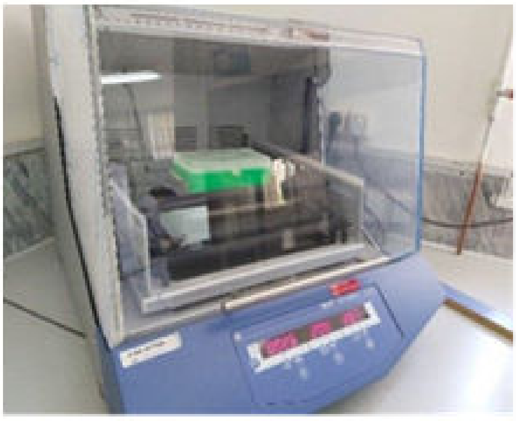

Figure 1. Incubator device.

Materials

In this study, the employed specimens were prepared using Portland cement type II possessing chemical properties given in Table 2. Tables 3 and 4 show the characteristics of the used aggregates, including crystal aggregate and black granite. The used sand in the study was determined with a unit weight of 2.704 gr/cm^3 and grains sieved through sieve no. 4 according to the standard ASTM C 136. Chemical analysis of the used leca in the mix design of the specimens is presented according to Table 5. In the present study, Table 6 shows the characteristics of the utilized micro silica with a unit weight of 2 gr/cm^3. In the mix design of the prepared specimens of this research, the used super plasticizer is with the base of polycarboxylate. Besides the mentioned materials in the mix design, air-entraining admixtures were used in some specimens with about 0.8% cement materials weight.

Chemical compounds	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
% amount	22/30	4/93	4/07	62/07	1/80	2/08	0/25	0/60

Table 2. Chemical analysis of used cement.

Chemical compounds	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO	TiO_2	K_20
%amount	%31	%14	%02	%57/75	%02	%61	%004	%02

Table 3. Chemical analysis of crystalline aggregate.

Abrasion resistance	porosity	Specific weight kg/m^3	Water absorption (%)
%3/3	13%	3/2	07

Table 4. Physical characteristics of black granite.

Chemical compounds	Sio_2	SiO_3	Fe_2O_3	CaO	Na_2O	MnO	MgO	TiO_2	K_2O	Al_2O_3	P_2O_5
%amount	66/05%	0.03%	7/10%	2/46%	69%	0.09%	61%	78%	2/69%	16/54%	21%

Table 5. Chemical analysis of lika seeds.

Silicon dioxide	Special Weight	Carbon	loss of blushing	Appearance
94/04%	250 gr/cm^3	05%.	1/44%	Gray powder

Table 6. Characteristics of microsilica used.

Mix design

This study determined the mix design in accordance with the ACI-211 guideline. The mixing ratio of the materials for 1 m^3 is given in Table 7.

Super lubricant	Microsilica	Leica	Black granite	Crystal aggregate	Sand	Cement	Water
4/5	50	535	116	154	268	450	175

Table 7. Mix design of specimens (kg/m^3).

Specimens

After the preparation process, specimens were protected 24 hours with a nylon cover to prevent moisture loss. After opening the mold, specimens were transferred to water pools with a temperature of 20°C ± 2°C. In this research, specimens were put into two different media consisting of water and water containing urea and calcium chloride to investigate the performance of specimens in different environmental conditions and the influence of the curing medium on the final results. After 28 days, specimens were taken out from pools, dried at ambient temperature, and transferred to an electric oven with 3 degrees/min heating rate. In this study, specimens were subjected to 150, 300, 450, and 600°C. Specimens were kept for about 1 hour in the oven to reach a stable thermal state. After the heat operations, specimens were transferred to ambient temperature to be cooled at the same rate so that compressive strength tests could be conducted after the completed cooling process.

Naming of specimens

In this study, specimens were labeled with two and three letters. For the two curing media (environments), including water and water containing urea and calcium chloride, the letters W and C were used, respectively. The letters B and A were used for specimens containing bacteria and air entraining admixture, respectively. For instance, the identification code W-B-A represented cured concrete in the water environment that contains bacteria and air entraining admixture. In addition, the letter R represented the reference concrete. For instance, the identification codes R-W and R-C stood for the cured reference concrete in water and water containing urea and calcium chloride, respectively. Table 8 shows the names of specimens and their curing media.

Results and Discussion

Compressive strength tests

The compressive strength test was performed according to the BS EN 12390 standard for the samples that were at ambient temperatures of 150-600-450-300 degrees celsius. The results after performing the compressive strength are shown in Table 8. Figure 2 shows the changes in the compressive strength of the samples.

Sample name	Processing environment	Ambient temperature	150°C	300°C	450°C	600°C
R-W	water	329	318	308	310	203
R-C	Calcium chloride and urea	312	300/8	291	296	199/8
W-A	water	349	180	165/9	176/4	154
C-A	Calcium chloride and urea	353/85	184	181	182	166/9
W-B	water	456	385/1	354/3	368	213
C-B	Calcium chloride and urea	480	403	380	391	220
W-B-A	water	305	164	130	158	128
C-B-A	Calcium chloride and urea	354	178	137	174	143/5

Table 8. Results of compressive strength of samples at different temperatures (MPa).

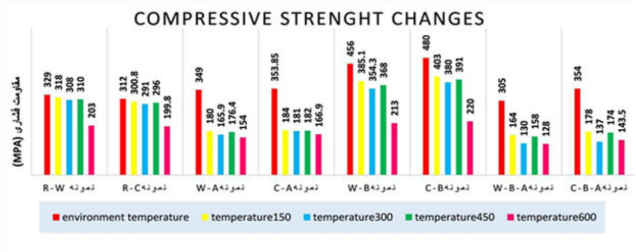

Figure 2. changes in the compressive strength of the samples after applying heat.

The obtained results from Figure 2 show a decrease in the compressive strength of all specimens subjected to heat. The compressive strength experiences a sharper reduction with an increase in the temperature. This case might be due to extensive changes in concrete's physical and chemical structure after subjection to high temperatures. Cracks occur on the concrete surface due to the physical water release and weakening of the intermolecular forces after being subjected to higher temperatures, which is an important factor in decreasing the compressive strength of specimens. In this investigation, in contrast to the expected results, the compressive strength of all specimens at 450°C increased compared to 300°C, which shows the hydration of cement particles that did not participate in the hydration process before reaching 450°C.

After investigating the compressive strength of two reference specimens, namely R-C and R-W, it was determined that the compressive strength of cured R-C in an environment consisting of calcium chloride and urea will start reacting 5% less than cured R-W specimen in an environment without reactants. Reduced compressive strength of R-C specimen, compared to R-W specimen, can be associated with the destructive nature of calcium chloride and urea for concrete structure. As can be seen from Figure 2, the maximum decrease in the compressive strength of the reference specimen is seen in the temperature 600°C, which is reduced by 35%-38% compared to their compressive strength in ambient temperature. Figure 3 the impact of air-entraining admixtures on compressive strength of specimens after the heating process

In the mix design, air entraining admixtures were added into specimens including W-A and C-A with about 0.8% cement materials weight. It was observed that adding this admixture will increase the concrete compressive strength, compared to reference specimens in ambient temperature. The reason for such event can be attributed to the fixed ratio of water to cement in the mix design of the specimens and the positive impact of using micro silica and the optimal value of air-entraining admixture utilized in the mix design of the specimens. In this research, the compressive strength of the specimen decreased significantly by applying heat on C-A-W-A designs. In other words, the compressive strength of W-A and C-A specimens decreased by 56% and 52% respectively at 600°C. As observed in Figure 3, the C-A specimen experienced a lower decline in terms of compressive strength compared to the W-A specimen. Also, after the heating process, the compressive strength of cured C-A specimen experienced a small decreasing trend in an environment consisting of calcium chloride and urea, and such event can be attributed to the trapping of calcium chloride and urea by air bubbles. Hence, generated air bubbles can limit the penetration of calcium chloride ions and urea into the concrete's structure as a destructive admixture.

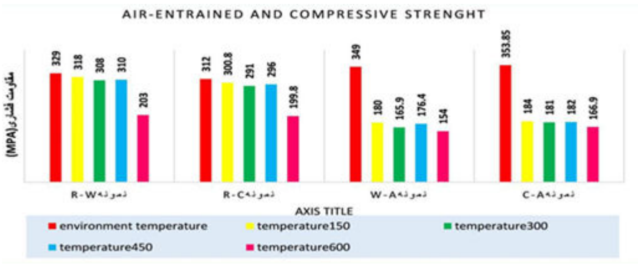

Figure 3. Effect of aeration on the compressive strength of the samples after applying heat.

The Impact of bacteria on concrete's compressive strength: As mentioned earlier, a strain of microorganisms with the capability to produce $CaCO_3$ precipitates and to repair the generated cracks inside the concrete's structure can have a great influence in increasing concrete's compressive strength. A review of Figure 4 in this study shows that using this biological method (adding bacteria to water considered for the mix design) causes a significant increase in compressive strength of W-B and C-B specimens. Compared to reference specimens, the compressive strength of W-B and C-B specimens increased by approximately 28% and 35% respectively. The findings depict the positive impact of an environment enriched with urea and calcium chloride for the specimens contain that contain bacteria, and the bacteria can have a more optimal activity for the production of solid crystals of $CaCO_3$. Filling pores inside the concrete with the aid of bacteria can cause the compressive strength of specimens to experience a lesser decline after the heating process, compared to specimens without bacteria. In other words, the compressive strength of bacterial specimens follows a lower declining trend compared to specimens without bacteria after being exposed to heat at different temperatures and this shows the effective impact of bacteria on the compressive strength of lightweight concrete, even after the heating process.

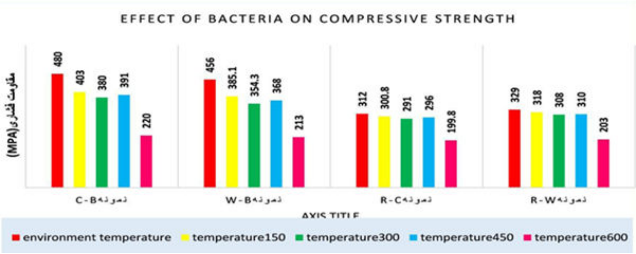

Figure 4. The impact of bacteria on compressive strength of specimens.

Comparing the influence of air-entraining admixtures on compressive strength of specimens containing bacteria *vs.* **without bacteria:** According to Figure 5, the simultaneous presence of bacteria and air entraining admixture in concrete specimens cause a decline in compressive strength, and compressive strength of bacterial specimens containing W-B-A bacteria decreased by almost 12.8% in ambient temperature compared to specimens without W-A bacterial. This event can be attributed to the trapping of *Sporosarcina pasteurii* inside the generated air bubbles and the presence of bacteria for a short period does not because the creation of $CaCO_3$ precipitates due to the non-existence of nutrients. Hence, as a result of this decline, the compressive strength of lightweight concrete declined. In addition to the results achieved by comparing compressive strength of two C-A and C-B-A specimens in ambient temperature, it can be found that simultaneous presence of bacteria and air-entraining admixture in a media enriched with $CaCO_3$ and urea does not have a significant impact on reducing compressive strength of specimens. This is because bacteria, which are trapped inside the air bubbles, continue their activities in a limited form in the ambient temperature to generate $CaCO_3$ precipitates due to the existence of $CaCO_3$ and urea nutrients. However, the result of achieved compressive strength does not depict an acceptable percentage of increasing compressive strength of specimens. Similar results are presented in Figure 6 and they depict that utilizing air-entraining admixtures in bacterial specimens causes a decline in compressive strength of specimens, meaning that compressive strength of W-B-A specimen decreased by 33% in ambient temperature compared to W-B specimen containing bacteria. The decreasing trend of compressive strength increases significantly by raising the temperature. Adding air-entraining admixture to C-B specimen containing bacteria cause a decline by almost 26% in compressive strength of specimen in ambient temperature, which is less than the value achieved by adding air-entraining admixture to cured concrete containing bacteria in water media by 6%. Hence, this shows that the negative performance of entraining admixture causes a lesser impact in the media containing $CaCO_3$ and urea in order to reduce the compressive strength of specimens.

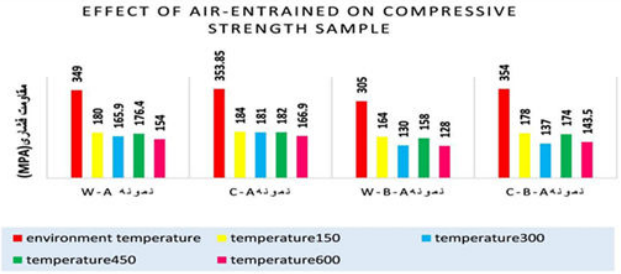

Figure 5. Effect of aerating agent on the compressive strength of bacteria-free and bacterial samples.

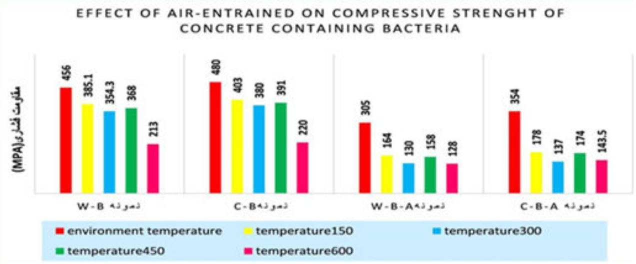

Figure 6. Effect of aerating agent on the compressive strength of bacterial concrete.

The impact of temperature on concrete appearance

The surface of specimens, which were exposed to high temperature, was reviewed and the first significant thing is the color change of specimens in different temperatures. There was no significant change in the specimens under the temperature of 150°C to 300°C but the color of specimens under the temperature of 300°C to 450°C changed to yellow-cream mix color and this can be explained by the oxidation of Fe_2O_3 that is present in the structure of Portland cement used in the mix design of light weight concrete (Figures 7 and 8). The second important thing in addition to color change (after being exposed to high temperature) is the growth of cracks on the surface of lightweight concrete. In high temperatures, the behavior of C-S-H dense nanostructures changes and this can cause cracks on the concrete surface that may grow gradually by increasing the temperature and the period of exposing concrete to heat. In turn, this will cause a decline in the compressive strength of specimens. Since the pores in specimens containing bacteria are filled with solid crystals of $CaCO_3$, the growth of cracks will be limited since $CaCO_3$ precipitates are capable of covering/filling small cracks on the surface of specimens.

Figure 7. Color changes of the samples after heating.

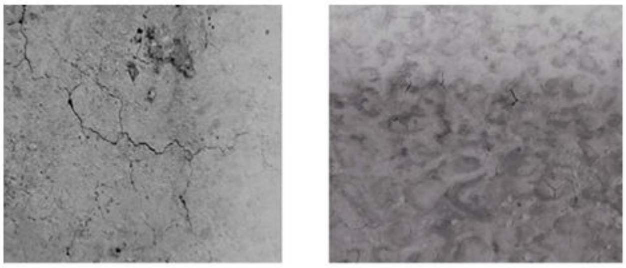

Figure 8. Comparison of the cracks created in the samples after heating.

Conclusion

This study shows the impact of temperature and bacteria on the compressive strength of lightweight concrete that was cured for 28 days in two different environments, including water and water containing calcium chloride and urea. The following results were achieved:

- Increasing the temperature causes a decline in the compressive strength of all specimens. By increasing temperature, the increasing trend of compressive strength in specimens containing bacteria will follow a lower declining trend. This can be explained by the effective role of solid $CaCO_3$ precipitates in filling the cracks and small cracks inside the lightweight concrete that have experienced a higher growth by increasing the temperature.
- Dense and durable Calcium Silicate Hydrate (C-S-H) that is present inside the concrete weakens and disintegrates gradually after exposure to high temperatures and this is also considered an important factor in decreasing the compressive strength of concrete and its disintegration. However, the existence of $CaCO_3$ precipitates in the structure of concrete containing bacteria can be a suitable alternative for C-S-H structures at an acceptable level since it can prevent the decline in compressive strength and concrete disintegration to an acceptable level.
- Utilizing bacteria in the mix design of specimens increased by almost 28% to 35% before exposing concrete to heat. The bacteria's performance to produce $CaCO_3$ precipitates, which is the main factor in increasing the compressive strength of specimens, depends on the media where specimens are cured. In other words, the bacteria present in the specimens cured in the environment containing calcium chloride and urea showed a more optimal performance to produce $CaCO_3$ precipitates, compared to specimens cured in an environment without reactants.
- The compressive strength of W-A and C-A specimens containing air entraining admixtures increased by almost 5.8% and 11.8% compared to compressive strength of reference specimens. By taking results into account, it was found out that air bubbles created inside the C-A specimen limits the penetration of calcium ions into the concrete's structure as a destructive admixture.
- Increasing the temperature caused the compressive strength of all the specimens containing air-entraining admixture to decrease and the compressive strength of W-A and C-A specimens decreased by 56% and 52% respectively at 600°C. The simultaneous presence of bacteria and air entraining admixture in the mix design of specimens caused a decrease in the compressive strength of concrete. In other words, the compressive strength of W-B-A and C-B specimens decreased by 33% and 26% respectably, compared to bacterial specimens without air-entraining admixture. The higher compressive strength of the W-B-A specimen can be attributed to the trapping of bacteria by air bubbles that are capable of decreasing bacteria activities to produce calcium precipitates in the environment without $CaCO_3$ and urea.
- Increasing the temperature will cause the color change of specimens due to the oxidation of Fe_2O_3 that is present in the structure of concrete. The high temperature not only causes the color change of specimens but also the growth of cracks due to the weakening of concrete. After reviewing the surface of bacterial specimens, covering of cracks caused by $CaCo_3$ precipitates is reported.

Authors Consideration

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Conflict of Interest

No conflicts of interest are reported between the authors.

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