DURABILITY PERFORMANCES OF COMPRESSED EARTH BLOCKS EXPOSED TO WETTING–DRYING CYCLES AND HIGH TEMPERATURE

PHILBERT NSHIMIYIMANA[1], CESAIRE HEMA[1], SEICK OMAR SORE[1,2],
OUSMANE ZOUNGRANA[1], ADAMAH MESSAN[1] & LUC COURARD[3]
[1]Laboratoire Eco-Matériaux et Habitats Durables,
Institut International d'Ingénierie de l'Eau et de l'Environnement, Burkina Faso
[2]Département Génie Civil de l'Institut Universitaire de Technologie, Université Nazi BONI, Burkina Faso
[3]Urban and Environmental Engineering, Université de Liège, Belgium

ABSTRACT

The environmental durability of earthen materials is among the main factors that limit their widespread acceptance in the contemporary building sector. This study assesses the performances of compressed earth blocks (CEBs) before and after exposure to the wetting–drying (WD) cycles and high temperature. The CEBs were produced from kaolinite-rich earth material stabilized with lime-rich residue (5%–25%) or the lime substituted with rice husk ash, lime:ash (20:0%–12:8%) or cement (4%–8%), with respect to the mass of dry earth. The CEBs were cured for 28–45 days and at the ambient temperature of a laboratory of 30±5°C and the moisture of production, necessary for the reactivity of the binders and improvement of the performances of CEBs. The CEBs were dried before testing their initial compressive strength. Their compressive strength was also tested after exposure to 12 cycles of wetting in water for 6 hours at 30±5°C and drying in the oven for 42 hours at 70±5°C. Additionally, it was tested after exposure to the elevated temperature of 150–600°C. After exposure to the WD cycles, the compressive strength of CEBs relatively increased, by up to 49% (4.6 to 6.8 MPa) for CEBs stabilized with lime (15%) and by up to 40% (4.4 to 6.2 MPa) with lime:ash (20:0%), with respect to their strength before the WD cycles. The maximum increase of the strength was observed for CEBs containing a higher amount of lime, related to the reaction of excess lime which resulted in the formation of more cementitious products and improvement of the strength of CEBs. Nevertheless, the compressive strength decreased by 55% (12.5 to 5.5 MPa) for the CEBs stabilized with cement (4%), resulting from the degradation of the initial cementitious products. However, the strength increased by up to 58% (4.2 to 6.6 MPa) for the CEBs stabilized with cement (8%) after exposure to 600°C. This implies that the stabilization of CEBs with lime-rich binder is more resilient to the WD cycles than cement. It also shows that the cement stabilized CEBs would at least retain their strength after exposure to high temperature.
Keywords: compressed earth blocks, chemical binder, compressive strength, high temperature, pozzolanic reaction, wetting–drying cycles.

1 INTRODUCTION

The improvement of the durability performances of earthen materials, and more specifically compressed earth blocks (CEBs) is essential for their widespread adoption in the building construction [1], [2]. Numbers of studies have reported that the different stabilisation using chemical industrial binders: cement and lime or alternative/by-product binders: geopolymer, lime residue or riche husk ash improve various engineering and durability indicators of CEBs [3]–[7].

Indeed, a very recent literature review has highlighted very interesting points on various advances currently made on the improvement of performance of stabilized CEBs [8]. The review also highlighted numbers of limitations and missing parameters of CEBs that still need to be addressed or tested, such as the lack of data on the "sound insulation and fire resistance properties", among other parameters. It was discussed that the performances of

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stabilized CEBs not only depends of the quality and the reactivity of the selected earthen materials, but also the conditions of production/ curing and testing [9], [10]. This suggests that the conditions of exposure would also affect the performances of CEBs.

In fact, few studies have investigated the behaviour of earthen materials after exposure to high temperature (fire). Beckett and Kazamias [11] were only interested in predicting the evolution of thermal behaviour of unstabilised rammed. Abdallah et al. [12] reported that the water content affects the thermal instability, while the cement stabilisation improves the thermal stability of earth. One study reported that increasing the firing temperature increases the compressive strength and reduces the abrasion coefficient of stabilised CEBs [13]. Moreover, some studies have shown that the CEBs stabilized with cement loss their strength after exposure to the wetting–drying (WD) cycles. The compressive strength decreased, from the value before to the value after the WD cycles, 0.3 and 0.5 times respectively when the CEBs were stabilized with 4% and with 8% cement [14], [15]. However, these studies did not assess the effects of exposure conditions on the engineering and durability performances of earthen materials, specifically the CEBs stabilized with by-product binders.

The present study reports on the preliminary results on the assessment of the performances of stabilized CEBs, when they are exposed to extreme conditions such WD cycles and high temperature. The current results are based on the evolution of the mechanical properties: the compressive strength of stabilized CEBs before and after exposure to such conditions. The present study specifically aimed to highlight the differences in the behaviours of stabilized CEBs depending on the type of chemical stabilizers, i.e. hydraulic binders: cement and lime versus pozzolanic binders: rice husk ash.

2 MATERIALS AND METHODS

2.1 Materials and methods for the production of CEBs

The present study was carried out using materials collected locally in the vicinity of Ouagadougou, Burkina Faso. The earthen material is a kaolinite-rich clay (60%) material collected from the site of Kamboinse (12°29’24.48” N; 1°32’59.28” W). The previous study have reported its physical, chemical and mineralogical properties [16]. The earthen material was stabilized with by-product binders for the production of stabilised CEBs. The lime residue (calcium carbide residue), collected from an acetylene production industry in Kossodo (12°25’56.1” N, 1°29’22.44” W). It was also stabilised using rice husk ash obtained by the calcination (500° for 2h) of the rich husk collected from Bagré (11°28’25.8” N, 2°03’21” W). The lime (residue) and the (riche husk) ash contain mainly hydrated lime ($Ca(OH)_2$) and amorphous silica, respectively, as it was reported in a previous study [17]. Moreover, the earthen material was stabilised with cement, CEM II 42.5 produced locally.

The CEBs were produced by mixing the earthen materials stabilized with 0 to 25% lime of the dry mass of the earthen material, 20:0 to 12:8% lime:ash and 4 to 8% cement. The dry mixtures were humidified with appropriate amount of water: 17 to 23% with lime or lime: ash, and 19% with cement, corresponding to the optimum moisture content of each mix. The humid mixtures were manually compressed in Terstaram press machine to produce stabilized CEBs: 29.5 × 14 × 9.5 cm^3 [18]. The curing was carried out in ambient conditions, at the production moisture, for 45 days and 28 days respectively for CEBs stabilised with lime or lime:ash [10] and cement [18]. The cured CEBs were dried to constant mass [5], before the treatment by exposure to various conditions.

2.2 Methods for the treatment and characterization of CEBs

The cured and dried CEBs were exposed to 12 cycles of wetting–drying. One cycle of WD is equivalent to 6 hours soaking in water (at ambient temperature: 30±5°C), followed by 42 hours drying in oven at 70±5°C. Afterward, the samples were dried to constant mass before testing their performances. The cured and dried CEBs were also exposed to higher temperature, in the range of 150–600°C, at the step of 150°C, by heating in a muffle furnace which has a maximum heating capacity of 3000°C. For all temperature of exposure, the heating rate was set at 1°C/min. A heating rate of 10°C/min was also applied to quickly reach the 600°C, in order to assess effect of higher heating rate on the performances of CEBs. The samples were maintained at the soaking temperature for 2 hours and cooled naturally in the furnace, before their characterization.

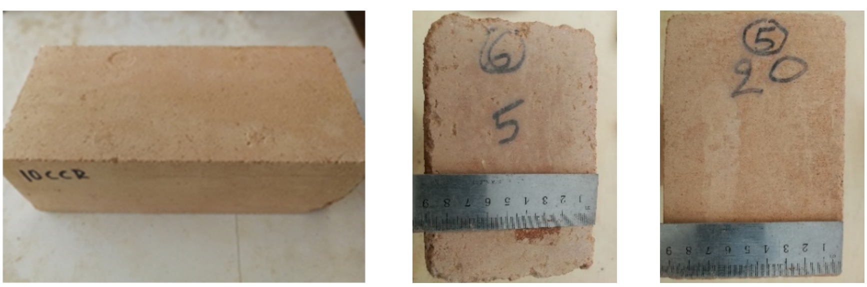
The CEBs were characterized based on their mechanical performances, tested before and after exposure to the WD cycles or the high temperature. The compressive strength was tested referring to the standard PR XP P13-901 [19], using hydraulic press equipped with a 300 kN capacity load cell, at loading rate of 0.2 mm/s. The compressive strength, Rc (MPa), was calculated using eqn (1); where Fr (kN) is the maximum load at failure and S (cm^2) is the area of loaded surface:

$$\text{Rc} = 10 \text{ x Fr/S}. \tag{1}$$

3 RESULTS AND DISCUSSION

3.1 Effect of exposure to the physical stability

The physical stability of the CEBs was affected by the exposure to both the wetting–drying (WD) cycles and high temperature. Fig. 1(a) shows that the CEBs were intact before the WD cycles. Fig. 1(b) shows the physical deterioration by the loss of particles on the edges of sample after exposure to the 12 cycles of WD, especially for the CEBs stabilized with low content of lime (5%). This is due to the weakening of the cohesion between particles. On the contrary, the CEBs stabilized with high content of lime (20%) maintained their physical stability after exposure to the 12 cycles of WD (Fig. 1(c)). Moreover, Fig. 2 did not show major physical change before and after exposure to high temperature, except the occurrence of radial crack on the surface of the CEBs (Fig. 2(c)). This may be related to the thermal shock felt in the CEBs due to the thermal gradient between the outside and the inside of the samples and/or the thermal shrinkage.



(a) (b) (c)

Figure 1: Samples of CEBs. (a) Before; vs (b) and (c) After 12 WD cycles, stabilized with 5% and 20% lime residue: deterioration of edges by the "loss of particle".

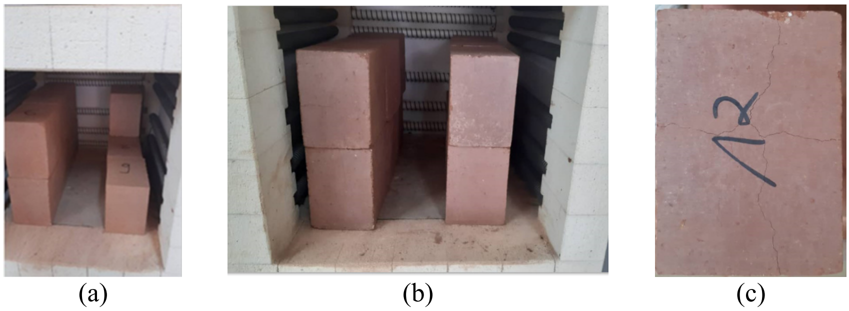


Figure 2: Samples in the muffle furnace. (a) Before; (b) After exposure to high temperature; and (c) Surface of samples after exposure to 600°C: occurrence of the “radial cracks” on surface.

3.2 Effect of exposure to the wetting–drying cycles on the mechanical resistance

The mechanical performance of the CEBs stabilized with lime-rich residue (5%–25%) increases, before and after the 12 cycles of WD, reaching the maximum value up to 10%–15% of lime content. The unstabilised CEB did not withstand the exposure to the WD cycles. The compressive strength increased from 3 to 4.6 MPa before the WD cycles and 3.5 to 6.8 MPa after the WD cycles for the CEBs stabilized with 5% to 15% lime (Fig. 3(a)). Fig. 3(a) shows that, for the same content of the lime, the compressive strength of stabilized CEBs improves with the WD cycles. This improvement is relatively as low as 17% (3 to 3.5 MPa) for lower content of lime (5%), contrary to the improvement of up to 49% (4.6 to 6.8 MPa) recorded for higher content of lime (15%). Fig. 3(b) further presents the values of the relative compressive strength: the ratio between the values after the WD cycles and before the WD cycles. It shows that the values of the compressive strength after exposure to the WD cycles are significantly higher (up to 1.5 times) than the values before the WD cycles.

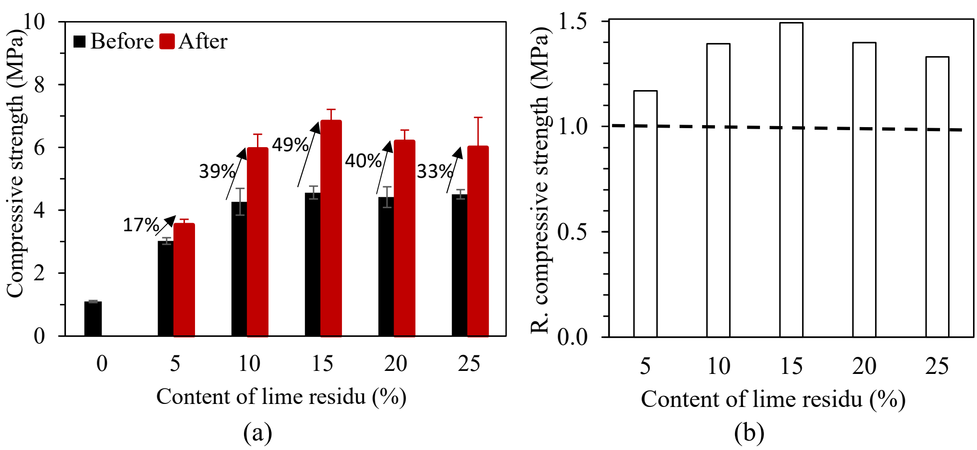


Figure 3: Compressive strength of CEB stabilized with lime. (a) Before and after 12 cycles of wetting–drying; and (b) Relative compressive strength: ratio between the values before and after WD cycles.

Fig. 4 presents the evolution of the compressive strength of CEBs stabilized with the mixtures of lime residue and rice husk ash in various ratios (lime:ash). It shows that the compressive strength increases with the ratio of lime:ash from 20:0 to 14:6 and decrease beyond, before and after the 12 cycles of WD. The average values of the compressive strength increased from 4.4 MPa to the maximum value of 8.4 MPa before the WD cycles and 6.2 MPa to the maximum value of 9.5 MPa after the WD cycles (Fig. 4(a)). The CEBs stabilized with 20:0% lime recorded the highest increase of the strength up to 40% (4.4 to 6.2 MPa) after the WD cycles. This shows that the compressive strength of CEBs is rather improved through the exposure the wetting drying cycles, as further presented in Fig. 4(b) where all the values of the relative compressive strength are greater than 1.

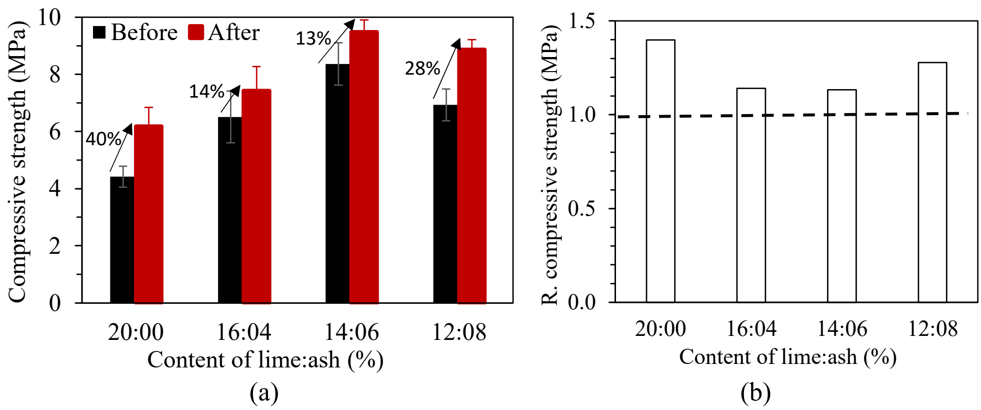


Figure 4: Compressive strength of CEB stabilized with lime:ash. (a) Before and after the 12 cycles of wetting–drying; and (b) Relative compressive strength.

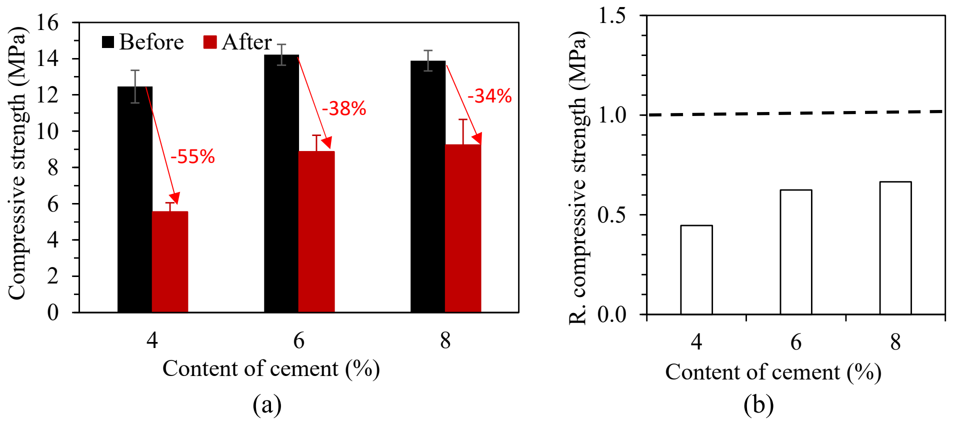


Figure 5: Compressive strength of CEBs stabilized with cement. (a) Before and after the 12 cycles of wetting drying of CEB; and (b) Relative compressive strength.

On the contrary, the compressive strength decreases for the CEBs stabilised with cement, as shown in Fig. 5. Fig. 5(a) shows that the average value of the compressive strength decreases by 55% from 12.5 to 5.5 MPa, 38% from 14.2 to 8.9 MPa and 34% from 13.9 to 9.2 MPa respectively for CEBs stabilised with 4%, 6% and 8% cement, before and after the WD cycles. It confirms that the exposure to the WD cycles degrades the mechanical performances of CEBs. This is further presented in Fig. 5(b), where the relative compressive strength remained far below 1 with all content of stabilization.

The increase of the compressive strength with the WD cycles, especially for CEBs stabilised with higher content of lime (≥ 15%) can be related to the effect of the treatment temperature (70°C) which, in the presence of the humidity, resulted in more reactivity in the CEBs matrix. This is also in agreement with the physical stability observed for the CEBs stabilized with 20% lime contrary to those stabilized with 5% clime, after exposure to the WD cycles (Fig. 1). In fact, the increase of the compressive strength of CEBs stabilized with the lime residue was previously related to the pozzolanic reaction between the earthen materials and the hydrated lime ($Ca(OH)_2$) contained in the residue [20]. At ambient temperature of curing, this reaction reaches the optimum with 10%–15% lime and so does the compressive strength. It was also reported that the kinetics of this reaction increase with increasing the curing temperature from 20°C to 40°C. It resulted in the increase of the compressive strength by 70% (2.3–3.9 MPa) and by 88% (2.5–4.7 MPa) respectively for CEBs stabilized with 10% and 20% lime residue [10]. This shows that the higher the content of lime, the more the effect of the temperature on the curing, and so does on the post-curing treatment. In the present study, the WD treatment, after the curing period, allowed for further reaction of the excess lime which did not successfully react during the curing and the increase of the compressive strength (Fig. 3). The same explanation can be made on the CEBs stabilized with the mixture of lime:ash, where the increase of the compressive strength was rather lower with the substitution of the lime residue by the rice husk ash (Fig. 4).

However, a different effect occurred for the CEBs stabilized with cement, which recorded a significant degradation of the compressive strength with the WD cycles (Fig. 5). Similar results were previously reported that the compressive strength of CEBs stabilized 4% and 8% cement respectively decreases by 0.3 times after six cycles of WD and 0.5 times after the 12 cycles of WD [14], [15]. The decrease of the compressive strength can be explained by the loss of the hydrates of calcium silicates and aluminates, previously formed during the curing of the stabilized CEBs. This results in the degradation of the cohesion in the matrix of CEBs and the loss of the strength.

3.3 Effect of exposure the high temperature on the compressive strength

Fig. 6 presents the evolution of the compressive strength of CEBs stabilised 8% cement, after exposure to the relatively higher temperature: from the ambient temperature of laboratory (30±5°C) to 600°C. It shows that the average values of the compressive strength did not significantly change from the ambient temperature up to the exposure temperature of 450°C, beyond which it increased. At 600°C, reached at gradual heating rate of 1°C/min, the average value of the compressive strength increased by 58% (4.2–6.6 MPa). Comparable results were recorded at 600°C, reached at rapid heating rate of 10°C/min, where the value of the strength increased by 46% (4.2–6.1 MPa) (Fig. 6(a)). It suggests that the CEBs stabilised with cement can at least maintain their strength up to 600°C. This is clearly shown in Fig. 6(b), where the relative compressive strength is around 1 up to 450°C and greater than 1 at 600°C. Similar observation is made on CEBs after exposure to 600°C reached at accelerated kinetics (10°C/min).

The strength of CEBs stabilized with cement after exposure to the temperature as high as 600°C, at both gradual and rapid increase is promising. This allows to predict that these CEBs

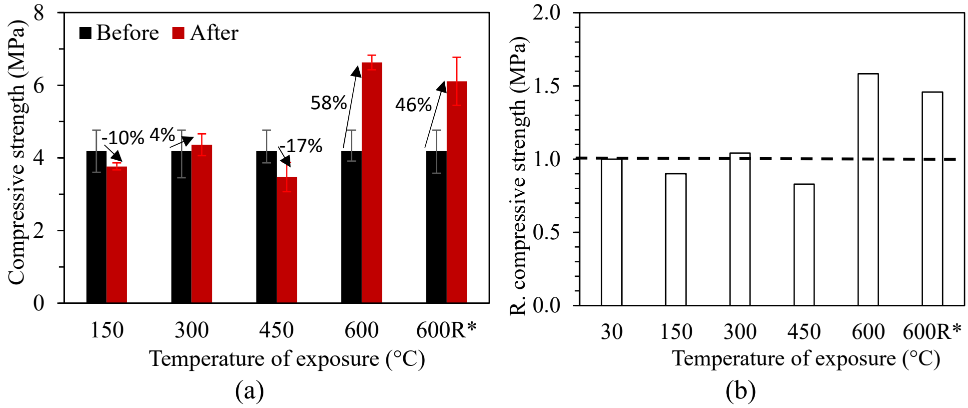


Figure 6: Effect of the temperature of exposure on: (a) The compressive strength; and (b) Relative compressive strength of CEB stabilized with 8% cement.

would potentially resist to the exposure at elevated temperature, such as in the case of fire, in agreement with [13]. On the contrary, the concrete would lose its strength and physical stability at high temperature (400–600°C) [21], [22]. It is also noteworthy highlighting the mechanical stability of CEBs in spite of their physical instability: occurrence of cracks on the surface of CEBs exposed to high temperature. However, these cracks may affect the transfer properties: porosity, water/vapor transfer in the CEBs. Therefore, they need further investigation.

4 CONCLUSIONS AND RECOMMENDATIONS

The present study assessed the performance of stabilized CEBs based on the evolution of their compressive strength before and after exposure to the wetting–drying cycles and high temperature. The following conclusions can be drawn:

- The compressive strength increases from 3 to 4.6 MPa for CEBs stabilized with 5% to 25% lime, before the WD cycles. It further increases from 3.5 to 6.8 MPa after the WD cycles, reaching the maximum with 15% lime. The highest increase of 49% (4.6 to 6.8 MPa) was recorded between the strength before and after the WD cycles.
- The compressive strength further increases from 4.4 to 8.4 MPa for the CEBs stabilized with 20:0 to 12:8% lime:ash, reaching the maximum with 16:4% lime:ash, before the WD cycles. It further increases from 6.2 to 9.5 MPa after the WD cycles. It recorded the highest increase of 40% (4.4 to 6.2 MPa) with 20:0% lime:ash, from before to after the WD cycles, highlighting the resistance to the WD cycles of CEBs stabilized with lime-rich binders.
- On the contrary, the compressive strength decreases for all content of cement after the WD cycles. The highest decrease reached 55% (12.5 to 5.5 MPa) for the CEBs stabilized with 4% cement, confirming the lack of the resistance to the WD cycles of the CEBs stabilized with cement.
- However, the compressive strength increases by up to 58% (4.2 to 6.6 MPa) for the CEBs stabilized 8% cement after exposure to the temperature of up to 600°C. This suggests that the CEBs can withstand the relatively high temperature without risking the loss of their mechanical performance.

This study shows that the mechanical performances of CEBs are influenced by the exposure to WD drying cycles and high temperature (up to 600°C) and the type of stabilizer. It is recommended that more studies assess other engineering and durability performances of CEBs and stabilized with different types of chemical binders, and specifically at the temperature higher than 600°C. This would allow to confirm whether the increase of the compressive strength is maintained beyond 600°C.

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