*African Journal of Rural Development*, Vol. 4 (3): July-September 2019: pp. 351-361. ISSN 2415-2838


# Effect of intrinsic clay soil composition on the properties of fired clay bricks

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## ABSTRACT

In many developing countries, clay bricks are manufactured by cottage industries with little regards to the intrinsic properties of the clay soil used. This study aimed at determining the properties of fired clay bricks fabricated under similar conditions from clay soils of varied intrinsic properties. The clay soils were collected from different locations in Kenya and their chemical composition analyzed using an Energy Dispersive X-ray Fluorescence. The bricks were fabricated using a consolidation pressure of 2.5 MPa, oven-dried at 100°C for 24 hours followed by firing at 1000°C for eight hours. The effect of chemical variation of zonal clay soils on the physical and mechanical properties of clay bricks was established. The determined properties of fired clay bricks investigated in this study emphasizes the need for thorough clay soil characterization and chemical properties standardization before producing bricks for structural applications.

Keywords: Brick shrinkage, clay brick porosity, clay composition, compressive strength

## RÉSUMÉ

Dans de nombreux pays en développement, les briques d'argile sont fabriquées par des industries artisanales sans considérer les propriétés intrinsèques du sol argileux utilisé. Cette étude visait à déterminer les propriétés des briques d'argile cuites fabriquées dans des conditions similaires à partir de sols argileux aux propriétés intrinsèques variées. Les sols argileux ont été collectés à différents endroits au Kenya et leur composition chimique analysée à l'aide d'une fluorescence X à énergie dispersive. Les briques ont été fabriquées en utilisant une pression de consolidation de 2,5 MPa, séchées au four à 100 C pendant 24 heures, puis cuites à 1000 C pendant huit heures. L'effet de la variation chimique des sols argileux zonaux sur les propriétés physiques et mécaniques des briques d'argile a été établi. Les propriétés déterminées des briques d'argile cuites étudiées dans cette étude soulignent la nécessité d'une caractérisation approfondie du sol argileux et d'une normalisation des propriétés chimiques avant de produire des briques pour des applications architecturales.

Mots clés: Retrait plastic de la brique, porosité de la brique d'argile, composition de l'argile, résistance à la compression

***Cite as:*** Githinji, D.N. 2019. Effect of intrinsic clay soil composition on the properties of fired clay bricks. *African Journal of Rural Development* 4 (3): 351-361.

Received: 01 August 2019
Accepted: 31 August 2019
Published: 30 September 2019

## INTRODUCTION

Clay soil is majorly composed of alumina ($A_l2O_3$) and silica ($S_iO_2$) in a layered structure (Kaolinite) that contains chemically bound water. In addition, it contains other compounds (usually oxides) of iron, calcium, sodium, barium, potassium, and also some organic and soluble matter (Murthy, 2002). The plasticity of clay when mixed with water is attributed to lubrication effect of water film adsorbed on the layered crystal structure of clay mineral. The evaporation of water during drying of water-clay mixture results in a rigid structure (green body). Firing of the green body at temperatures above 1000°C results in vitrification where a liquid glass is formed from the alumina, silica, free oxides and fluxes in the clay material. The liquid glass flows around the remaining un-melted particles and fills in the pores as a result of capillary action. On cooling, a glassy matrix is formed by the fused phase resulting in a dense, strong body. The final microstructure of the fired clay product thus consists of a vitrified phase, any un-reacted quartz particles, and some porosity (NPCS Consultants, 2007).

The formation of clay soil is a natural process and therefore its chemical composition may vary depending on the geological and environmental conditions (Bergaya and Lagaly, 2013). Since the production of a fired clay product is based on a chemical process, its mechanical and physical properties may vary depending on the chemical composition of the clay soil used. As reported by (Okunade, 2008), clay soil with different physical properties produces fired clay bricks with varying densities, compressive strength and porosity. A study on ancient clay bricks from different regions, reported a variation in their chemical, physical and mechanical properties (Lourenço *et al.,* 2010). Consequently, it is important to understand how inherent chemical variations of different clays impact on the properties of fired clay bricks. This may thus assist in developing standardization protocols for clay soil chemical composition so as to allow the safe usage of fired clay bricks in load bearing applications.

Most studies on the characterisation of clay brick focuses on the physical and mechanical properties (Baronio and Binda, 1984; Baronio and Binda, 1985; Dondi *et al.,* 1999; Elert *et al.,* 2003; Sedat *et al.,* 2006) with little regard to the effect of composition on such properties. In Kenya, clay brick is a popular building material in the rural areas owing to its availability, durability and affordability compared to other building materials such as concrete blocks. However, majority of these clay bricks are produced from cottage industries and their physical and mechanical properties have been reported (Ayoro and Osemo, 2015; Shihembetsa and Madete, 2018) to vary from region to region. To ensure safety of clay bricks as a building material, it is important to establish the reasons behind these variations. Since clay soil is a natural product with inherent chemical variations, its application for clay brick manufacture requires a systematic study to ascertain the effect of such variations on the brick's properties. This is the aim of the current study, where fired clay bricks were made under similar conditions using chemically characterized clay soils obtained from different locations in Kenya with varied weather patterns, vegetation, soil formations and altitudes. The bricks were then characterized to determine their mass density, colour, apparent porosity and compressive strength.

## MATERIALS AND METHODS

**Study area.** The current work is based in Kenya which lies between latitudes 4° N and 4° S and between longitudes 34° E and 42° E. The country has climatic and ecological extremes with altitude varying from sea level to over 5,000 m in the mountain region. The climate is warmer and humid along sea level regions and gradually becomes cooler towards the highlands. The mean annual rainfall ranges from less than 250 mm in semi-arid and arid areas to more than 2,000 mm in high potential areas (Mariara and Karanja, 2007; Ayugi *et al.*, 2016). The country can be divided into three broad climatic zones: humid, sub-humid and arid. Humid zones in Kenya have an altitude of over 1,500 m and receive an annual rainfall in excess of 1,000 mm (Mariara and Karanja, 2007; John and Onyando, 2013). They have volcanic rocks and their soils are formed through laterization process where heavy precipitation results in rapid weathering of rocks with basic cations of silica and some alumina leaching from the upper soil profile. Iron and aluminium compounds, however, are not leached out. In volcanic areas, soils also contain volcanic materials such as ash, pumice and cinders. Under humid conditions, these materials hydrolyze to form aluminium and silica rich materials such as allophane and imogolite (under high rainfall) or halloysite (under low rainfall) (Jones *et al.*, 2013). Volcanic soils and alluvial soils are also rich in carbonates (Verheye, 2009). Sub-humid zones in Kenya have slightly less rainfall than the humid areas (John and Onyando, 2013). They have volcanic and basement rocks and lie between 1000 to 1500 m above sea level with red clay and loamy sandy soil types (Mariara and Karanja, 2007). These areas experiences soil calcification owing to evapo-transpiration where ground water containing dissolved alkaline salts rises to the surface due to high temperatures. Thus, the soil in this zone exhibits high accumulations of calcium carbonate (lime), dehydrate calcium sulphate (gypsum) and silicon dioxide (silica) (Pidwirny, 2006). Semi-arid and arid zones in Kenya receives on average 300–500 mm of rainfall annually and are characterized by shallow soils developed mainly from sedimentary rocks (Mariara and Karanja, 2007; John and Onyando, 2013). In this study, fired clay bricks from different locations in Kenya were evaluated to determine the effect of clay soil chemical composition on physical and mechanical properties of bricks.

**Materials**. Clay soils studied were collected from five different locations in Kenya where brick making was an economic activity. These locations have different weather patterns, vegetation, soil formations and altitudes. Zone sampling method was used to identify locations for clay soil collection. The clay soil samples were collected at altitude of 17 m in Mombasa, 2100 m in Eldoret, 1500 m in Maseno, 1800 m in Nakuru and in Nairobi at altitude of 1650 m above sea level. From each location, five clay soil samples weighing 5 kilograms were collected at depths of 40 cm (Njoka, 2015) through manual digging. The collected soils from each location were then mixed using quartering technique to obtain a representative sample. The samples were then sun-dried to constant weight, ground and sieved using a metallic mesh of 3.25 mm apertures. The sieved samples were then coded as S1, S2, S3, S4 and S5 following the collection locations given above and also shown in Figure 1.

**Determination of clay soils chemical composition**. Chemical composition of the clay soil samples was determined using an X-Ray Fluorescence (XRF) analyser. From each location, five random samples of ground clay soil weighing 50 grams were analysed and average chemical composition reported. The elemental analysis was based on characteristic fluorescent X-rays emitted by elements in the clay soil when irradiated using X-ray. From the X-ray spectrum generated, the positions of the fluorescent X-ray peaks allowed qualitative identification of the elements present while the intensities of the peaks allowed quantitative determination of elemental composition. The instrument was calibrated using a standard sample with known concentrations (%wt.) of elements. The relative weight composition was therefore determined by relating the heights of peaks obtained from the standard sample to those obtained from the clay soil sample. Quantitative data computation and reporting was done entirely by the XRF instrument. For each clay sample, the cumulative weight percentage of all elements therein added to 100%. Since clay soil contain many elements, only major elements that are known to affect brick's performance such as silica, alumina, lime and iron oxide (Gani *et al*., 2015) were presented in this work. The cumulative weight percentage of these major elements was greater than 98% for most of the samples analyzed. A One-way ANOVA was used to analyze the chemical composition data obtained from different locations to check if they were statistically different. The analysis was conducted at 95% confidence level and p-values reported.

**Production of clay bricks**. The ground and sieved clay soil was mixed with water and kneaded to form a smooth plastic paste. The paste was poured into 80 mm x 50 mm x 50 mm mould and compacted at 2.5 MPa for 5 minutes using a hydraulic compressing machine (Githinji *et al*., 2015). The green bricks were dried in an oven for 24 hours at a temperature of 100 C. The dried bricks were then fired at 1000˚C for 8 hours in a furnace followed by slow cooling inside the closed furnace for about 12 hours. In this study, each clay soil sample from a given location was used to produce 10 bricks and only average values are reported. The fabricated clay bricks were given similar coding as their corresponding clay soil samples.

**Determination of mass density and porosity of the fired clay bricks**. The mass density was calculated from the measured mass and volume of the fabricated clay bricks. The dimensions were determined following Kenya Standard KS EAS 54:1999 (KeBS, 1999). The determination of apparent porosity was based on the net mass gain of oven-dried clay bricks soaked in boiling water (Duggal, 2009). The apparent porosity was given by the ratio of the volume of water absorbed to the volume of the saturated clay bricks.


**Figure 1. A map of Kenya showing locations where clay soil samples were collected. (Adopted from Google map)**

**Determination of compressive strength of the fired clay bricks**. Determination of dry compressive strength of the fired clay brick was conducted following Kenya Standard KS EAS 54: 1999. Whole brick samples were tested in a uniaxial testing machine set in a displacement controlled mode. A constant crosshead speed of 2.5 mm/min was used and the height/width ratio of the brick was more than 1.5. This ratio was sufficient to minimize the boundary effect during the compression test. By dividing the peak compressive load by the original cross-sectional area of the brick, the compressive strength was obtained.

## RESULTS AND DISCUSSION

**Clay soil chemical composition**. The chemical composition (wt. %) of clay soil samples collected from different locations in Kenya is given in Table 1. Only the major compounds in the clay samples are indicated. It is evident from the results that the chemical composition of clay soils from different locations is significantly different at 95% confidence level ($p<0.05$). The variation of clay soil composition in different regions has also been reported by (Njoka, 2015). Different compounds found in clay have diverse effects on the properties of fired clay bricks. Silica prevents shrinkage, cracking and warping of raw bricks and its typical range is between 50-60% (wt.). Alumina affects the plasticity of wet aluminosilicates clay and a high content results in excessive shrinkage and warping of bricks (Punmia *et al.,* 2003). Lime serves to reduce brick's shrinkage on drying and also enhances fusing of silica during firing which binds bricks particle together. Iron oxide plays a role in the ultimate colour of the fired clay brick.

Clay collected from S4 region had the highest silica content which may be attributed to volcanic soil found in the region. The relatively high calcium carbonate in region S5 may be ascribed to reduced mineral leaching owing to limited rainfall and presence of black cotton soil in the region. Since alumina is an amphoteric substance which reacts with bases and acids, it relatively high content in region S1 may be attributed to relatively low base content in the soil in this region compared to other regions. The reported variation in chemical compositions in this study can be attributed to differences in factors such as climatic conditions, soil formation mechanism and underlying rocks types (Neall, 2002; Pidwirny, 2006; Saat *et al.,* 2009).

**Fired clay bricks physical properties.** A comparison of mass densities of the fabricated clay bricks from different regions in Kenya is shown in Figure 2. The differences in mass densities may be ascribed to variation in alumina content of the clay soils studied. Clays are aluminosilicates, being composed of alumina ($Al_2O_3$) and silica ($SiO_2$) that contain chemically bound water (Bergaya and Lagaly, 2013). Aluminosilicates have a layered crystal structure on which water molecules forms a thin lubricating film thus contributing to plasticity of

**Table 1. XRF chemical composition (wt. %) analysis of clay soils**

| Compounds | Locations in Kenya | | | | | |
|---|---|---|---|---|---|---|
| | S1 | S2 | S3 | S4 | S5 | p value |
| Alumina ($Al_2O_3$) | 23.7 | 21.8 | 19.0 | 12.1 | 18.2 | < .00001 |
| Silica ($SiO_2$) | 71.4 | 60.0 | 73.0 | 81.1 | 72.8 | < .00001 |
| Lime (CaO) | 0.5 | 0.3 | 0.5 | 0.5 | 0.7 | < .00001 |
| Iron oxide ($Fe_2O_3$) | 2.0 | 3.3 | 3.1 | 2.6 | 4.0 | < .00001 |
| Potassium oxide ($K_2O$) | 1.7 | 3.2 | 3.2 | 2.5 | 3.1 | < .00001 |

P value is based on One-Way ANOVA analysis at 95% confidence level the clay soil. The higher the aluminosilicate content the more plastic is the clay and subsequently the higher the shrinkage and mass density owing to evaporation of large amount of water during drying. As reported by Olajide *et al*. (2015), aluminosilicate content of the clay soil affects bulk density, porosity and shrinkage of the fired clay bricks. As shown in Table 2, brick samples from region S1 had the highest alumina content and mass density while samples from region S4 had the lowest alumina content and mass density. The mass densities of these two samples were found to be significantly different.

The variation in mass densities of the clay bricks may also be attributed to presence of voids within the brick structure. As seen in Table 2, an increase in mass density occurs as the fraction of void in the brick structure decreases. Voids in fired clay brick may arise when organic matter and/or compounds in the clay decomposes during the firing stages. In a previous study, porosity in clay brick was linked to clay soil composition (Cultrone *et al*., 2004). It is possible that sample S4 had a high content of decomposable matter owing to its large apparent porosity compared with other brick specimens. Additionally, the high apparent porosity could have been due to limited fusing of silica owing to reduced content of $K_2O$ which serves as a modifier oxide. Consequently, the voids in the fired bricks remain unfilled. The effect of apparent porosity on the overall mass density is significant between S4 bricks and the other bricks as seen in Figure 2 and Figure 3. Importantly, the determined porosities were

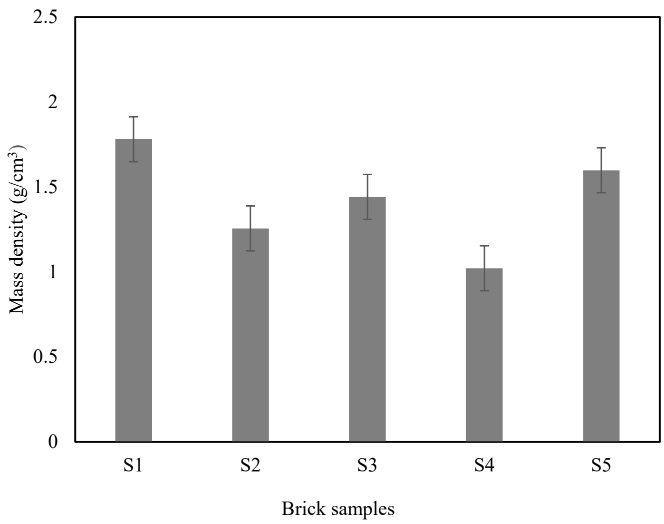



**Figure 2. Mass densities of clay bricks obtained from different locations in Kenya. The indicated error bars are based on standard deviation of the measurements**

**Table 2. Fired clay bricks properties**

| Sample | Mass density (g/cm3) | % Porosity | Alumina content (wt. %) |
|---|---|---|---|
| S1 | 1.78 | 0.16 | 23.7 |
| S2 | 1.26 | 0.11 | 21.8 |
| S3 | 1.44 | 0.17 | 19.0 |
| S5 | 1.59 | 0.17 | 18.2 |
| S4 | 1.02 | 0.24 | 12.1 |

within the range reported previously (Engineers, 2007; Phonphuak, 2013). The variation of mass density of clay bricks has also been previously linked to composition of clay and porosity (Phonphuak, 2013).

Table 3 relates the colour of the fabricated clay bricks to their iron oxide content. From the qualitative colour assessment of the clay bricks, dark shades were obtained at relatively high iron oxide content. This can be attributed to 'earthy' colour of this oxide in nature. Several studies have linked the colour of fired clay bricks to their iron oxide content (Kriemeyer, 1987; Fernandes *et al.*, 2009; Ingham, 2013). The colour of clay brick is also a function of firing temperature as reported by Karaman *et al*. (2012). However, in this study the firing temperature was kept constant and therefore the observed variation in colour may be attributed to iron oxide content.

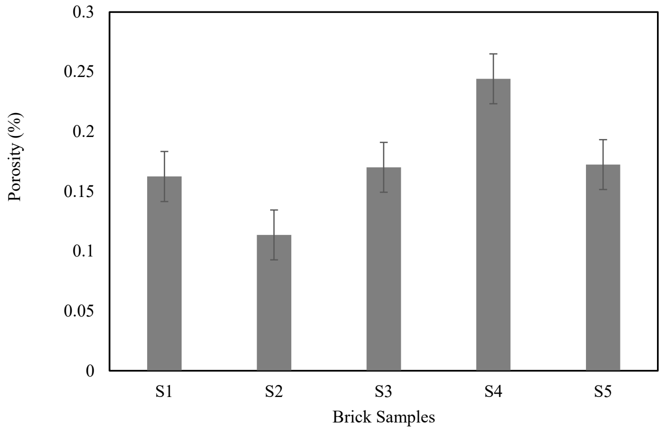
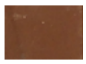
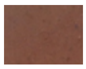



**Figure 3. Porosity of clay bricks made with clay soils obtained from different locations in Kenya**

**Table 3. Variation of fired clay brick colour as a function of iron oxide content**

| Sample | Colour | Iron oxide content | Brick's colour |
|---|---|---|---|
| S1 | Yellow- orange | 1.98 |  |
| S2 | Orange | 2.34 |  |
| S3 | Orange- red | 3.10 |  |
| S4 | Brown- red | 2.64 |  |
| S5 | Dark- red | 3.91 |  |

**Characterisation of clay bricks.** Figure 4 shows the compressive strength of the fabricated bricks from different locations in Kenya. Compressive strength of bricks is an important engineering property since it allows them to be stacked vertically together during construction. A higher compressive strength increases other properties such as flexure and resistance to abrasion. From the results, bricks from region S2 had a significantly higher average compressive strength than those made from region S1, S3, S4 and S5. This difference may be attributed to its relatively low silica content compared to the other clay soils studied. Silica is a non-plastic ingredient of clay which occurs as finely ground quartz. The quartz experiences little change during firing owing to its high melting temperature. The presence of large amount of un-reacted quartz particles in the final microstructure of fired bricks may reduce their compressive strength owing to limited bonding of clay particles by the vitrified phase. It is possible, therefore, that the relatively low compressive strength of S1, S3, S4 and S5 bricks may be as a result of their premature brittle failure during the loading cycle owing to their relatively high silica content. Additionally, the S2 brick had relatively low apparent porosity, which may have reduced initiation and propagation of cracks during loading thus increasing its load carrying capacity. Porosity and clay soil composition have been shown previously to influence compressive strength of the clay brick (Baiden *et al.,* 2014; Milyaso *et al.,* 2015; Olajide *et al.,* 2015). It is clear from the results that the mean compressive strengths of bricks from different regions were significantly different at 95% confidence level ($p<0.05$) as shown in Table 4. This result, therefore, underpin the importance of clay soil composition on the final compressive property of fired clay bricks. The standardization of the clay soil composition through controlled addition of various clay soil compounds is necessary for uniform properties in the fired clay bricks produced at cottage industries. Notably, the clay soil from Eldoret (S2) produces the best clay bricks for construction industries since their average compressive strengths (14 MPa) were better than that specified by EAS 54:1999 Standards (7 MPa) for ordinary construction bricks. The determined compressive strengths also agree with literature findings (Okunade, 2008; Fernandes *et al.,* 2009; Lourenço *et al.,* 2010; Milyaso *et al.,* 2015; Olajide *et al.,* 2015).

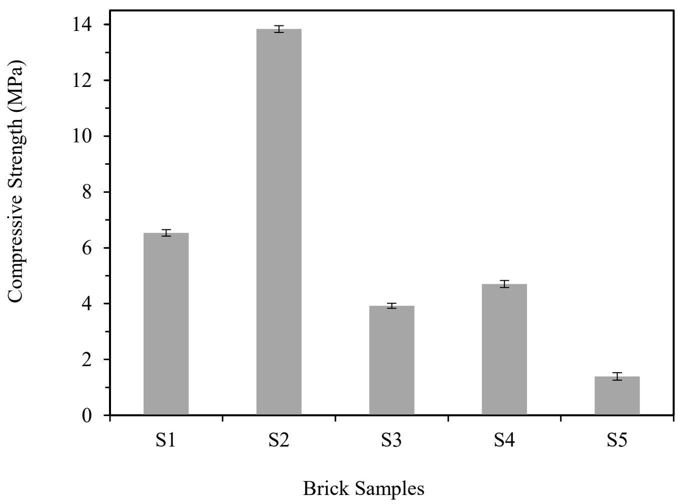



**Figure 4. Compressive strengths of fired clay bricks made with clay soils obtained from different locations in Kenya**

Table 4. One-way ANOVA analysis of compressive strength of bricks from different locations in Kenya

| Source | SS | df | MS | |
|---|---|---|---|---|
| Between locations | 444.4714 | 4 | 111.1178 | F = 47243.97959; $p < 0.00001$ |
| Within locations | 0.047 | 20 | 0.0024 | |
| Total | 444.5184 | 24 | | |

## CONCLUSION

In this study, fired clay bricks were made using clay soils with intrinsic chemical variations. The soils were collected from different locations in Kenya having varied weather patterns, vegetation, soil formations and altitudes. Fabrication was conducted under similar conditions and the resultant bricks characterized in terms of their physical and mechanical properties. From the study, the following conclusions are drawn:

- Clay soils from different locations have significantly different chemical compositions thought to arise from climatic and geological variations of these areas. The main compounds in the clay soils studied are silica, alumina, iron oxide, potassium oxide and lime, in a decreasing order of weight percent. The clay soils with the highest amount of silica, alumina, iron oxide, potassium oxide and lime were found in Maseno, Mombasa, Nairobi, Eldoret and in Nairobi region, respectively.
- Clay chemical composition has a significant effect on physical properties of bricks. High alumina content increases brick's shrinkage during drying resulting in an increase in brick's mass density. Clay soil from Mombasa region has the highest alumina content and produces bricks with the highest mass density compared to bricks from other locations studied. The final colour of fired clay bricks depends to a large extend on the iron oxide content of the clay, with dark shades obtained at relatively high iron oxide content.
- Clay chemical composition has a significant effect on the compressive strength of fired clay bricks. Clay soil with relatively low silica content produces bricks with relatively high compressive strength and low apparent porosity. Clay soil from Eldoret region has the lowest silica content and produces bricks with the highest and required compressive strength compared to bricks from other locations studied. The bricks from this region are therefore the most suitable for load bearing applications in construction industries.

The variation of fired clay brick properties as a function of intrinsic composition of clay soil used, underpin the importance of clay soil characterisation and chemical properties standardization prior to production of bricks for structural applications.

## ACKNOWLEDGEMENT

The author thanks Kenyan Ministry of Mining for their assistance in conducting chemical analysis of the clay soils. The author also acknowledges Barbara Kwena and Ivy Mudaki for assisting with the experimental work and ACEII-PTRE of Moi University for providing laboratory equipments. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## STATEMENT OF NO-CONFLICT OF INTEREST

The author declares that there is no conflict of interest in this paper.

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