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COMPRESSION DEFORMATION BEHAVIOUR OF FIRED SHALE-GANGUE PERFORATED BRICK MASONRY

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Abstract

By the experimental research of compression deformation behaviour of fired shale-gangue perforated brick masonry, this paper adopts respectively 3 modes of expression to regress and analyze the compression stress—strain relationship of this type of masonry. And also this paper discusses and recommends the reasonable values of elastic modulus, Poisson ratio and peak strain of this masonry.

Key Words

Fired perforated brick, Stress—strain curves, Elastic modulus, Poisson ratio.

1 Foreword

The deformation performance, one of the basic mechanical performances of masonry, is an important factor for structural analysis, anti-seismic calculation and finite unit analysis. But until now, there is little research on the stress-strain relationship of this type of masonry. The host important parameters of the deformation performance of the brick masonry, such as the Poisson ratio, elastic modulus and compression peak strain are based on the researches of the solid clay brick masonry (Code for Design of Masonry Structure GB50003-2001, 2002). But the deformation performance has connection with the masonry materials. As a structural material, fired shale-gangue perforated brick masonry has been researched and popularized in many places in recent years, because of its fine building physical performance. So it is necessary to do systemic research on the basic mechanical performance. By researching the compressed specimens of this masonry under monotone loading, finding out its developing process of the compression deformation and analyzing the influence of the brick material, geometry dimension and the aperture ratio on the deformation performance of this masonry, this paper establishes a reasonable stress-strain relationship, and probes into the appropriate values of the Poisson ratio, elastic modulus and peak strain.

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2 General situation of experiment

2.1 Design of the masonry specimens and experiment measures

The type of the fired shale-gangue perforated brick used in the experiment is KP1 (240 ×115×90mm) (Code of Fired Perforated Brick GBJ13544-1992, 1992),roundness aperture:20 mm, aperture ratio: 22.8%.

There are perforated bricks in 4 strength grades and blend mortar in 5 strength grades, which are arranged in 20 groups, 4 specimens in each group and 80 specimens in total in this experiment. According to the demands of the Code for Experiment of Basic Mechanical Property of Masonry GBJ129-90, (1994), the design dimension is 240× 370×800 mm (length×width×height), the mortar thickness is 10 mm and the ratio of the height of specimens to the width is 3.33. The experiment begins after the specimens have all been conserved for 28 days indoors. The test instruments are arranged as Figure 1. There is a micrometer instrument on each of the vertical midline of the broad side face of the specimen to measure the longitudinal compression deformation. The gauge length equals the width of two bricks and two horizontal mortar slots, about 250 mm. There is a micrometer instrument on each of the horizontal midline of the broad side face of the specimen to measure the transverse deformation. The gauge length is about 230 mm, over a vertical mortar slot. An X-Y function register draws the curve of the relationship of the experimental load in time on the specimens and the experimental longitudinal deformation in time.

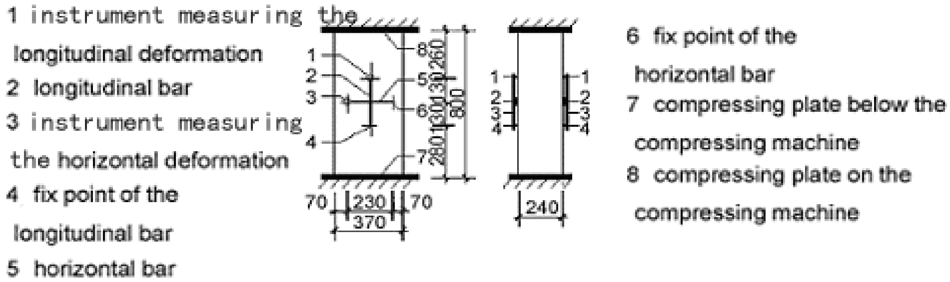

Figure 1 Sketch map of the experiment and test instrument

Before experiment, re-compression which is 10~20% of the predicted ultimate load is needed to eliminate the compression deformation of the sand layer under the specimen and carry out the physical alignment. If the relative error of the longitudinal deformation of the two side faces of the specimen is more than 10%, the specimen's position or the horizontal level should be re-adjusted. Load should be added step by step and each grade load is about 10% of the predicted load, which should be completed in 1~1.5min, and held on for 1~2min for reading.

2.2 Phenomenal description of the experiment

Similar to ordinary solid brick masonry, the axial compression deformation course of the perforated brick masonry can be divided into 3 courses. When the load is less than 50% of the ultimate load, the longitudinal deformation increases linearly and the load-deformation curve （$s/f_m \sim e/e_0$） presents linear relationship, which indicates that the masonry is in elastic phase. When the load is about 50~85% of the ultimate load, the single brick which lies around the middle vertical mortar slot, 2/3 of the height of the specimen in the narrow face, crazes firstly,. The crack will stop expanding if the load is stopped. When the load is about 85% of the ultimate load, the cracks in the single brick will expand and connect, and the cracks that run through several bricks will come into being, which indicates that the compression course is in the second phase. The character of this phase is that the cracks will go on expanding and new cracks will

appear, even if the load will not be added, deformation（e/e_0）will increase fast and fast, and load-longitudinal deformation curve presents curving evidently. As the load is added, there is bomb sound inside the specimen, and each crack widens and expands into a vertical main crack. When the load is close to the ultimate load, because of the fast development of the cracks, the transverse deformation increases rapidly, and even exceeds the vertical deformation. When the load reaches the ultimate load, the specimen is hacked into some small columellas and destroyed with noise. And soon the load decreases rapidly. It presents much more evidently brittle than ordinary solid brick.

3 Result and analysis of the experiment

3.1 Relationship of the experimental average stress and strain

According to the experimental values of specimens under each grade load, the average values of s/f_m , e and e/e_0 of each group of specimens are listed in Table 1, which shows the relationship of average stress and strain. The value of s/f_m is increased by 10%.

Table 1 only lists the ascending phase of the relationship of stress and strain, because the micrometer instrument can only measure the value of compression deformation of specimens before the ultimate load.

Table 1 Relationship of the experimental average stress and strain

s/f_m	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
e/e_0	0.0205	0.047	0.0725	0.1025	0.1485	0.207	0.2745	0.362	0.534	1

3.2 Idealization of the relationship of stress and strain

Scholars at home and abroad have brought forward many expressions of the constitutive relationship of the stress and strain of masonry, including logarithmic expression, exponential expression, polynomial expression, rational-fraction expression and so on. And the idealization of the relationship of stress and strain is a math expression to describe the deformation of masonry. The whole curve can be expressed in one equation, or in two equations respectively to indicate the ascending phase and the descending phase. Because only the peak value of the load is noted in the experiment, the analysis of the experiment data of $s/f_m \sim e/e_0$ pays attention to the ascending phase in this paper. Regress-analyze in three modes as follows:

3.2.1 Logarithmic expression type

A scholar of pre-Soviet Russia brought forward an logarithmic expression in the 30's (Guiqiu Liu et al, 2000)：

$$e = -\frac{1.1}{z}\ln(1-\frac{s}{1.1f_k}) \qquad (1)$$

z is the elastic characteristic value related to the type of the block and the strength of the mortar；

f_k is the criterion value of the compression strength of masonry.

"Relationship of Stress And Strain of Masonry under Compression" (Guiqiu Liu, et al, 2000) considers that the definition of 1.1 f_k in the expression is reluctant, and z doesn't reflect the effect of the strength of blocks. Basing on exp. 1, according to the results of statistics and analysis of experiment data, "Relationship of Stress And Strain of Masonry Under Compression" (Guiqiu Liu et al, 2000) puts forward ameliorative expression (that is also the expression in the Code for Design of Masonry Structure

GBJ3-88 (1994)) in which average value f_m of compression strength of masonry is the basic variable:

$$e = -\frac{1}{z_1\sqrt{f_m}}\ln(1-\frac{s}{f_m}) \qquad (2)$$

Table 2 Value of z_1

Strength of brick		9.05 (MPa)	24.54 (MPa)	28.18 (MPa)	36.30 (MPa)
Strength of mortar	2.83(MPa)	903	516	313	306
	7.79(MPa)	625	435	591	350
	8.66(MPa)	864	698	432	339
	12.96(MPa)	582	328	316	338
	15.08(MPa)	550	411	359	363

According to statistical analysis of the experiment data, the value of z_1 equals to 460. The experiment data is regressed by least square according to the model of exp. 2 in this paper, and the calculating values of z_1 are in Table 2. Because that when $s/f_m = 1$, e trends infinite, the experiment data corresponding to $s/f_m = 1$ is not included in regression. The constitutive relationship of σ ～ ε gained by regression can be expressed in two expressions as follows:

ⅰ. When the strength grade of brick is on the low side (the average value of z_1 corresponding to 9.05 MPa grade):

$$e = -\frac{1}{704\sqrt{f_m}}\ln(1-\frac{s}{f_m}) \qquad (3)$$

ⅱ. When the strength grade of brick is on the high side (the average value of z_1 corresponding to 24.54, 28.18, 36.30 MPa grade):

$$e = -\frac{1}{406\sqrt{f_m}}\ln(1-\frac{s}{f_m}) \qquad (4)$$

But the average value of z_1 in each group equals 480, close to z_1=460 in "Relationship of Stress And Strain of Masonry under Compression" (Guiqiu Liu, et al, 2000). However, there are several questions after exp. (2), (3), (4) are analyzed carefully:

① z_1 decreases with the increment of the strength of the brick ,which is shown in Table 2, and decreases with the increment of f_m also. So, it is unreasonable to make z_1 constant. However, by contrasting expression (1) and (2), it is obvious that z corresponds with $z_1\sqrt{f_m}$, meanwhile z_1 and $\sqrt{f_m}$ vary opposite to the variation of f_m, so, z the product of z_1 and $\sqrt{f_m}$ should be constant.

② After comparison of the experiment value and the regress value of strain gained by exp. (3) and (4) under each grade of s/f_m, the difference between regress value and experimental value increases with the accretion of s/f_m, which indicates that regress exp. (3) and (4) function well when the compression stress of the masonry is on the low side, but not very well when the compression stress is on the high side.

③ When s/f_m is close to 1, the value of e is close to infinite, which does not agree with the fact. In the process of calculation, it is discovered that when $s/f_m = 0.9 \sim 1$, the strain develops very fast and it can reach 40% of the peak strain. When $s/f_m = 1$, the experiment data is abandoned in regression, so it leads to great error. Totally, this

paper puts forward the ameliorative expression that is based on exp. (1), and expressed in relative strain as follows:

$$\frac{e}{e_0} = -\frac{1.1}{z}\ln(1-\frac{s}{1.1f_m}) \tag{5}$$

Regress the experiment data by least square:

$$\frac{e}{e_0} = -0.34\ln(1-\frac{s}{1.1f_m}) \tag{6}$$

When $e/e_0 = 1$, and s/f_m =1.042≈1, exp. (6) is much more reasonable than exp. (2). According to exp. (6), the standard deviation equals to 0.10.

3.2.2 Parabolic expression in one section

Parabolic expression in one section is usually used in academic research: $s/f_m = A\frac{e}{e_0} - B(\frac{e}{e_0})^2$, thereinto: A, B are undetermined coefficients. And exp. (7) can be got by regress-analysis of the experiment data in this paper:

$$\frac{s}{f_m} = 3.08\frac{e}{e_0} - 2.1(\frac{e}{e_0})^2 \tag{7}$$

This expression has several characteristics as follows:

① The form is simple and it is convenient to calculate in the parabolic expression, but this expression can not distinguish the phase characteristics in the process of compression deformation of the masonry, such as the fast development of the strain after the appearance of cracks in the masonry.

② When e/e_0 =0.73 but not 1, the stress reaches the peak value. It's an obvious error. The main reason is that the strain resulted by the last one or two grades of stress is developing too fast to be expressed in expression (7). So this constitutive relationship is not suitable.

③ According to expression (7) and the experiment data, the standard deviation equals to 0.19.

3.2.3 Expression of relationship of stress and strain in two sections

Totally, this paper brings forward the expression of relationship of stress and strain in two sections, also considers the relationship of experimental stress and strain and the characteristics of compression deformation: when s/f_m ≤0.5, the first section adopts beeline, known as $s/f_m = ke/e_0$, the k in which is a regress coefficient; when 0.5< s/f_m ≤ 1.0, the second section adopts parabolic type, known as $s/f_m = C + A\frac{e}{e_0} - B(\frac{e}{e_0})^2$, the A, B, C in which are all regress coefficients. Substitute the experiment data into the expressions above, thus:

$$s/f_m = 3.81e/e_0 \quad \text{(when } s/f_m \leq 0.5\text{)} \tag{8}$$

$$s/f_m = 0.26 + 1.85e/e_0 - 1.11(e/e_0)^2 \quad \text{(when } 0.5 < s/f_m \leq 1.0\text{)} \tag{9}$$

Analysis indicates that when e/e_0 =0.833, the stress reaches the peak value, which is closer to the fact than that by the parabolic expression in one section. In the fact, when 0.5< s/f_m ≤1.0, the parabolic expression of relationship of stress and strain should satisfy the three boundary conditions below:

① when s/f_m →0.5, e/e_0 →0.5/3.81=0.13, it means that it should intersect with the first beeline at this point;

② when s/f_m =1, e/e_0 =1;

③ when e/e_0 =1, s/f_m reaches the maximum.

Substitute these boundary conditions above into $s / f_m = C + A\frac{e}{e_0} - B(\frac{e}{e_0})^2$, thus:

$A = 1.32, B = 0.66, C = 0.34$. So, when $0.5 \le s / f_m \le 1.0$:

$$s / f_m = 0.34 + 1.32 e/e_0 - 0.66(e/e_0)^2 \quad (10)$$

Substitute the experiment data into exp. (8) and (10). Thus, the standard deviation equals to 0.09. According to the comparison, the parabolic expression of relationship of stress and strain in two sections fits the experiment value better than that in one

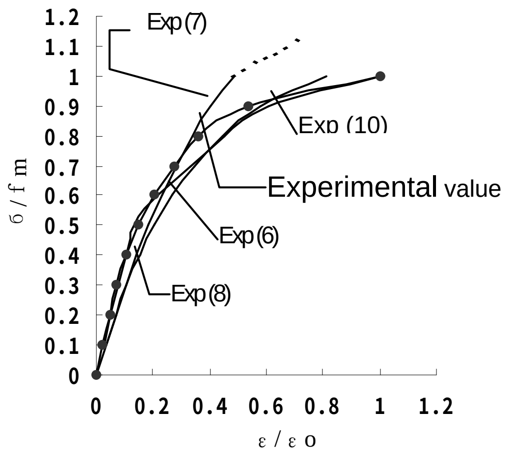

Figure 2 Experimental values of stress and strain and the sublimate curve

section, and can represent the characteristics of compression deformation of the masonry in different phases, while the form is simple and it is easy to use. And it is considered as a preferable constitutive relationship of the stress and strain of the shale-gangue perforated brick masonry. The three expressions of the relationship of the stress and strain exp. (6), (7), (8) (10) and the experiment values are all depicted in Figure 2 for comparison.

3.3 Elastic modulus of the perforated brick masonry

3.3.1 Experimental elastic modulus

The elastic modulus E_m is an important index of the deformation behaviour of masonry. This experiment adopts the monotonously loading measure. According to the result of "Elastic Modulus of Compression of Masonry" (Chuxian Shi, April 1989), the elastic modulus measured during the monotone loading is just 7% less than that measured after the repeating loading. And the elastic modulus of masonry, defined by the Code for Experiment of Basic Mechanical Property of Masonry, GBJ129-90 (1994) equals the secant modulus when $\sigma = 0.4 f_m$ under monotone loading. The experimental average values of the elastic modulus of each group are in Table 3. In this table, f_m is the average value of the compression strength of the masonry in each group. According to Table 3, there is an obvious connection between the average value E_m of elastic modulus and average value of compression strength f_m . E_m ascends with the accretion of f_m. Regress-analyze the experiment data in $E_m = a f_m \sqrt{f_m}$ mode as follows:

$$E_m = 367.68 f_m \sqrt{f_m} \quad (11)$$

It is close to the experimental result of the solid clay brick masonry. The result of the solid clay brick masonry $a = 370$, in “Elastic Modulus of Compression of Masonry” (Chuxian Shi, April 1989), which indicates that as the elastic modulus, there is no

Table 3 Experimental average values of the elastic modulus E_m^t and average values of compression strength f_m (unit: MPa)

Strength of mortar		2.83	7.98	8.66	12.96	15.08
		$\frac{E_m^t}{f_m}$	$\frac{E_m^t}{f_m}$	$\frac{E_m^t}{f_m}$	$\frac{E_m^t}{f_m}$	$\frac{E_m^t}{f_m}$
Strength of brick	9.05	5863.1 4.30	5109.6 4.37	6674.0 4.39	6179.2 4.43	5756.5 4.52
	24.54	9364.0 8.40	9695.0 9.09	16046.9 10.19	13026.3 11.47	17123.9 12.19
	28.18	10973.7 9.50	12989.9 10.33	14122.9 11.95	19528.3 13.10	18866.8 14.66
	36.30	15107.3 11.21	13538.4 11.67	19816.8 13.05	23304.0 16.96	23563.5 17.29

great difference between the fired shale-gangue perforated brick masonry and the solid clay brick masonry. The Code for Design of Masonry Structure GB50003-2001 (2002) and Code for Design of Masonry Structure GBJ3-88 (1994) in China adopts that there is a direct ratio between E_m and f_m: $E_m = kf_m$. According to the strength of the mortar, this paper also adopts this formula to regress the experimental values. The values of the proportion factor k are in Table 4*.*

Table 4 The proportion factor k

Strength of mortar	2.83(MPa)	7.98(MPa)	8.66(MPa)	12.96(MPa)	15.08(MPa)
k	1237.76	1168.34	1421.77	1356.15	1345.41
Average value	1203			1374	

According to the average value k of the mortar group on the low strength side and the mortar group on the high strength side, respectively E_m is:

$$E_m = 1203 f_m \tag{12}$$

$$E_m = 1374 f_m \tag{13}$$

3.3.2 Recommended value of the elastic modulus

The standard deviation is 251.73 and 286.62 respectively, and the variance coefficient d equals 0.21. So, the criterion value of the elastic modulus that bears 95% factor of assurance is:

$$E_k = (1203 - 1.645 \times 251.73) f_m = 789 f_m \quad \text{(Mortar on the low strength side)} \tag{14}$$

$$E_k = (1374 - 1.645 \times 286.62) f_m = 903 f_m \quad \text{(Mortar on the low strength side)} \tag{15}$$

To compare with the code, according to “Elastic Modulus of Compression of Masonry” (Chuxian Shi, April 1989), $f = 0.52 f_m$ and considering that the present Code for Design of Masonry Structure, GB50003-2001, (2002) enlarges the material subentry coefficient from 1.5 to 1.6, so $f = \frac{1.5}{1.6} \times 0.52 f_m$. Substitute them into exp. (14) and (15):

$$E = 1618 f \approx 1600 f \quad \text{(Mortar on the low strength side)} \tag{16}$$

$$E = 1852 f \approx 1800 f \quad \text{(Mortar on the low strength side)} \tag{17}$$

f is the design value of compression strength of the masonry.

The index of the elastic modulus in the present Code for Design of Masonry Structure, GB50003-2001, (2002): when the strength of the mortar equals M2.5, $E = 1300f$; when it equals M5, M7.5, or M10, $E = 1600f$. It mainly bases on the experiment result of the solid clay brick. Not only the material of the perforated brick used in this experiment differs from the code, but also the height of the brick (90 mm) is thicker than that of ordinary solid clay brick, which lessens the horizontal mortar slot of the masonry and reduces the longitudinal compression deformation, so the elastic modulus is larger than that of solid clay brick masonry

3.4 Poisson ratio of the perforated brick masonry

Divide the experimental horizontal deformation of masonry under progressive load by gauge length, namely the value of transverse deformation e_{tr} of the masonry, and Poisson ratio v can be figured out according to the formula as follows:

$$v = e_{tr} / e \qquad (18)$$

e is the experimental value of the longitudinal deformation of the masonry under progressive load

The relationship of the progressive stress ratio s / f_m and the corresponding Poisson

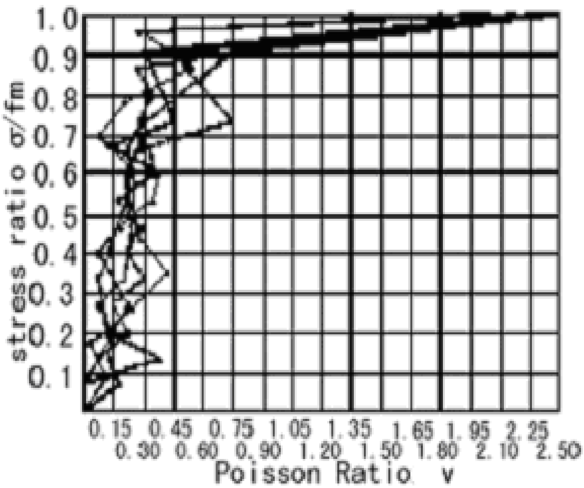

Figure 3 Relationship of experimental $s / f_m \sim v$

ratio v is in Figure 3. It indicates that there is great discreteness between the values of v of each specimen, and v distributes in a large area. But it shows the change tendency of v: when s / f_m < 0.7～0.8, although the experiment values spread around relatively, the average experiment value is quite stable, no more than 0.35; when s / f_m > 0.8, because the horizontal deformation of masonry increases rapidly, faster than that of longitudinal deformation, v lost the practical meaning. According to the Code for Experiment of Basic Mechanical Property of Masonry, GBJ129-90, (1994), the Poisson ratio $n_{0.4}$ equals the Poisson ratio of the specimen when s / f_m =0.4. According to stat. analysis, $n_{0.4}$ of the perforated brick masonry in this experiment lies in 0.1～0.3, and the recommended average value 0.15, equals to that in “Experiment Research of Poisson Ratio of Brick Masonry “(Ruxin Hou, April 1989).

3.5 Peak strain of the perforated brick masonry

Peak strain, the longitudinal strain when the compression stress reaches its maximum, is an important parameter of the relationship of stress and strain of masonry. The average values of the experimental peak strain e_0 of each group are in Table 5. The

average value of the experimental peak strain equals 0.0031, (variation coefficient is 0.18) close to the value e_0 =0.0033 found in "Experimental Research of the Stress-strain Curve of the Shale-gangue Brick Masonry" (Xueyou Quan, Shaoliang Bai, 1999)

Table 5 Average value of the experimental peak strain e_0

Strength of mortar		2.83 (MPa)	7.79 (MPa)	8.66 (MPa)	12.96 (MPa)	15.08 (MPa)
Strength of brick	9.05(MPa)	0.00250	0.00285	0.00265	0.00273	0.00275
	24.54(MPa)	0.00363	0.00288	0.00268	0.00378	0.00345
	28.18(MPa)	0.00313	0.00283	0.00313	0.00308	0.00375
	36.30(MPa)	0.00270	0.00338	0.00265	0.00380	0.00278

4 Conclusion

①The process of compression deformation of the fired shale-gangue perforated brick masonry can be divided into 3 phases, and the constitutive relationship of stress and strain can be expressed in two sections by a straight segment (exp. 8) and a curved segment (exp. 10). Analysis indicates that the fit degree and the rationality are better than that of a logarithmic expression and the parabolic expression in one section. And the connection expression is simple and it is easy to use.
②There is a distinctive connection between the average value of experimental elastic modulus E_m and average value of compression strength f_m , and there is little difference between the curve regress expression (exp. 11) and that of solid clay brick masonry. But the value of linear regress expression is more than the value of present code a little. The main reason is that the height of KP1 perforated brick is higher than that of ordinary solid brick, which reduces the relative horizontal mortar slot of the masonry.
③The experimental values of Poisson ratio are discrete evidently, and it distributes in a large area. When $s / f_m = 0.4$, the value of Poisson ratio $n_{0.4}$ lies in 0.1～0.3. The average value 0.15, advised to adopt, equals to that in "Experimental Research of Poisson Ratio of Brick Masonry" (Ruxin Hou, April 1989).
④There is little connection between the peak strain e_0 and f_m .The averaged value of the experimental peak strain is 0.0031, (variance coefficient is 0.18) close to the value e_0 =0.0033 of the shale-gangue solid brick masonry found in "Experimental Research of the Stress-strain Curve of the Shale-gangue solid Brick Masonry" (Xueyou Quan, Shaoliang Bai, 1999).

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