Design of Flexible Road Pavements as Affected by Drainage Conditions

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ABSTRACT

Road pavement use is determined primarily by the vehicle type that will use the facility. Climatic conditions affect the behavior of pavement materials, as well as the sizes of traffic loads. The relative strength loss in a layer due to its drainage characteristics and the total time it is exposed to near-saturation moisture conditions is represented by drainage coefficients. The Transportation Laboratory of Democritus University of Thrace in Xanthi Greece has developed an algorithm for a computer-based procedure towards the calculation of the layer thickness of flexible pavements. The design equation used is that described by the American Association of State Highway and Transportation Officials. The present work deals with the effect of drainage on the total thickness of the structure as it directly influences the cost of large infrastructure projects like roads. The output of different cases solved is presented in table and schematic form. Changes in technology related to pavement design and construction practices will necessitate revisions to currently used computing techniques. There is a need for computerized methodologies for thickness design of flexible asphalt pavements (granular base course) for a wide variety of pavement uses providing users the capability to conduct structural analysis of special pavement structures. Improvements in computing times which will affect the cost of computerized methods available to engineers are to be suggested in the near future. Empirically supported pavement designs used nowadays in Greece require modifications based on regional experience and on a better assessment of the drainage conditions prevailing in each area crossed by a roadway project. Since design considerations constantly change, it is obligatory to shift towards more sophisticated design methods.

Keywords: *flexible pavement, thickness, design, software, drainage conditions*

INTRODUCTION

Under the influence of various factors, the bearing capacity of an in service pavement deteriorates, thereby downgrading its service level. Such factors, beyond the engineering characteristics of the materials, are the effect of traffic volume (especially the percent of heavy vehicles) and the environmental/climatic conditions, which contribute to the aging of materials.

In a recent research work [1] the author has suggested that it is possible to estimate equivalent single-axle loads (ESALs) values through the use of artificial neural networks. As a massively parallel distributed processor, a neural network has a natural tendency to store experiential knowledge and make it available for use. Thus, the complex design equation of American Association of State Highway and Transportation Officials (AASHTO) which over-estimates the number of ESALs would not be necessary and the coefficients given in this way could obtain the actual load values (better calculation of design traffic input).

The AASHTO flexible pavement design method has been compared with other design methods to check the appropriateness of its predictions on the performance of pavements in their service-life. Such a comparison has been made against the National Cooperative Highway Research Program - NCHRP Project 1-37A mechanistic-empirical approach for a variety of locations with different climate, subgrade properties, and materials [2]. This research effort has shown that the AASHTO guide overestimates performance (suggesting reduced distress) at high traffic volumes and warm places.

The KENLAYER software [3] from the KENPAVE suite of programs for pavement analysis and design has been used [4] along with the results of AASHTO design guide and the Mechanistic-Empirical based computer program Road Note 31 which has been developed by the Transport Research Laboratory, TRL, UK and predicts fatigue cracking of the pavement [5]. The conclusion of that research was that although there has been a good agreement for the predicted capacity of the pavement structure with the two methods, significant difference appeared when the KENLAYER was employed.

Different ideas to improve the concept of flexible pavement design posed by AASHTO have been proposed [6, 7]. Some of them have been realized both in experimental stages and in everyday practice [8, 9]. The use of specialized software makes it easier to compare the results, find any drawbacks or highlight the positive options of these newer design procedures.

Purvis [10] in 2013 analyzed the output of StreetPave, WinPas and I-Pave software packages in order to define the sensitivity of pavement thickness due to various design factors used as input parameters. For the aforementioned work –that was limited to low volume roads- the AASHTO design was used as a guide. The ARA (Applied Research Associates, Inc.) is an employee-owned scientific research and engineering company. They have evaluated the I-Pave Low Volume Road Design Software, having AASHTO design method as a standard for comparison [11]. As a result, it came up that the thickness for flexible pavement calculated by the I-Pave Software is identical to that from the AASHTO design equation.

In an effort to study the effect of the moisture condition in the unbound layers of a pavement structure, the drainage coefficients of base and sub-base have been considered as dependent variables and a computer software has been constructed in Democritus University of Thrace Transportation laboratory. Some of the applications are described in the following sections and the output is presented in graphical form.

STRUCTURE OF SOFTWARE CONCEPT

In 1962, the AASHO Road Test, run in USA by the Highway Research Board, established a correlation equation for the pavement structure as a function of traffic, soil condition, and change in pavement condition. With the AASHTO design the pavement performance is related to downgrading of the pavement ride quality or serviceability caused by the increase of traffic volumes or by aging over time.

In Eq. (1) the traffic is represented by the W_{18} term which is expressed as Equivalent Single Axle Loads 18,000 lb (80 kN). The terms Z_R and S_0 have been added later as reliability and variability factors, respectively, in order to describe the pavement's ability to function under the design conditions given as inputs. Both terms act in reality as safety factors. The soil condition is quantified by its resilient modulus, M_R.

The quantities taking part in the Eq. (1) are regression coefficients which can be altered if newer data become available through in situ testing and different prevailing conditions. These regression coefficients provide the best fit between SN, ΔPSI and M_R on one hand and the expected performance of the pavement on the other hand. The performance is expressed in ESALs.

$$\log_{10}(W_{18}) = Z_R \cdot S_0 + 9.36 \cdot \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \cdot \log_{10}(M_R) - 8.07 \tag{1}$$

where:
W_{18}= estimated 18-kip (80 kN) ESALs accumulated over the life of the project
Z_R= standard normal deviate
S_0= standard deviation
SN= structural number
ΔPSI= change in serviceability
M_R= resilient modulus

The required Structural Number (*SN*) or the associated pavement layer thickness is based on the relationship in Eq. (2). *SN* determines the total number of ESALs that can be borne by a particular pavement structure. In the design process, the quality of drainage is incorporated through the introduction of coefficients, m_i, into the structural number equation

$$SN = \alpha_1 \cdot D_1 + m_2 \cdot \alpha_2 \cdot D_2 + m_3 \cdot \alpha_3 \cdot D_3 \tag{2}$$

where:
ai= layer coefficient of the i-th layer (i=1, 2, 3)
Di= layer thickness of the i-th layer (i=1, 2, 3)
m_2, m_3= drainage coefficient of the base and sub-base layers respectively

For the greatest accuracy possible, Eq. (1) and Eq. (2) should simultaneously be solved.

In general, the drainage coefficients are thought to be representative of the strength loss in a pavement layer because of its drainage characteristics, as well as of the total time the material of the layer is exposed to near-saturation moisture levels. An engineer designing a proper pavement may take into consideration a value higher from the commonly assumed for routine materials when drainage conditions are favorable; on the other hand a decreased drainage coefficient would cover poor drainage conditions.

For the materials of base and sub-base, two different drainage coefficients are to be used. A pavement system with good drainage characteristics will be assigned with m_i values higher than 1.0. Good characteristics are those permitting the pavement to be drained quickly, a day or less will be enough time, while it is near the saturation for a little time-period (<1%). Obviously, this time depends on the mean annual rainfall and the prevailing drainage conditions. In a scenario where the water drains in a day and the period of saturation conditions is 1%, the drainage coefficient could be assumed taking a value of 1.3. In the case where the water will take 1 month to drain and the pavement is exposed to moisture levels approaching the saturation more than 25% of the time, then the drainage coefficient will be well smaller than 1.0, let's say 0.60. The value of 1.0 could be assigned to a material needing a week to drain.

INFLUENCE OF THE DRAINAGE COEFFICIENTS ON THE LAYER THICKNESS

In order to study the effect of drainage coefficients on the thickness of unbound base and sub-base layers a software algorithm has been constructed which solves for the basic

AASHTO Eq. 1 when it is supplied with input data consisted by the expected traffic volume for a 20 year design period reduced to 80 kN equivalent ESALs. The pavement terminal serviceability index, P_t, the reliability, R, and the standard deviation, S_0, are also required. Next, the user provides the resilient moduli of the layers as well as the drainage coefficients estimated for the unbound base and sub-base layers. The moduli are converted inside the program to layer coefficients, α_i. The program using an iterative procedure calculates and presents as outputs the individual thicknesses, *Di*, and the respective structural numbers for the different layers based on Eq. (3), (4) and (5).

$$D_1^* \geq \frac{SN_1}{\alpha_1} \qquad SN_1^* = \alpha_1 \cdot D_1 \geq SN_1 \tag{3}$$

$$D_2^* = \frac{SN_2 - SN_1^*}{\alpha_2 \cdot m_2} \qquad SN_1^* + SN_2^* \geq SN_2 \tag{4}$$

$$D_3^* \geq \frac{SN_3 - \left(SN_1^* + SN_2^*\right)}{\alpha_3 \cdot m_3} \tag{5}$$

where the asterisk indicates the really used value of the quantity after its rounding to the next half of the unit used and which has to be greater or equal to required one.

The procedure for the calculation of the layer thicknesses takes into account the limitations posed by fiscal and construction distresses as a function of the traffic volume to be served during the service life of a road project. Minimum thickness values for the expected traffic intensity have been suggested by AASHTO and are presented in Table 1.

Table 1 Minimum thickness values as a function of traffic

Traffic (ESALs)	Asphalt concrete (mm)	Aggregate Base (mm)	Sub-base (mm)
<50,000	25	100	100
50,001-150,000	50	100	100
150,001-500,000	65	100	100
500,001-2,000,000	75	150	150
2,000,001-7,000,000	90	150	150
> 7,000,000	100	150	150

In order to simplify the calculations, in this work the hypothesis has been made that the base and sub-base drainage coefficients are equal to each other and that they range between 0.5 and 1.4 (higher value of the drainage coefficient means better drainage conditions).

In Figure 1 the effect of drainage coefficients, m_i, on the base and sub-base thicknesses D_2, and *D3*, respectively is presented. The influence on the total thickness of the pavement structure is also depicted in Figure 2. The problem solved in the presented case included a subgrade modulus, M_R, equal to 5,000 psi (34 MPa), the expect traffic volume in 18-kip (80 kN) ESALs equal to 5,000,000, the terminal serviceability index, P_t=2.5, reliability R=95% and standard deviation, S_0=0.35. The Marshal stability value is taken equal to 2000, while the base and sub-base moduli 50,000 psi (344 MPa) and 15,000 psi (103 MPa), respectively.

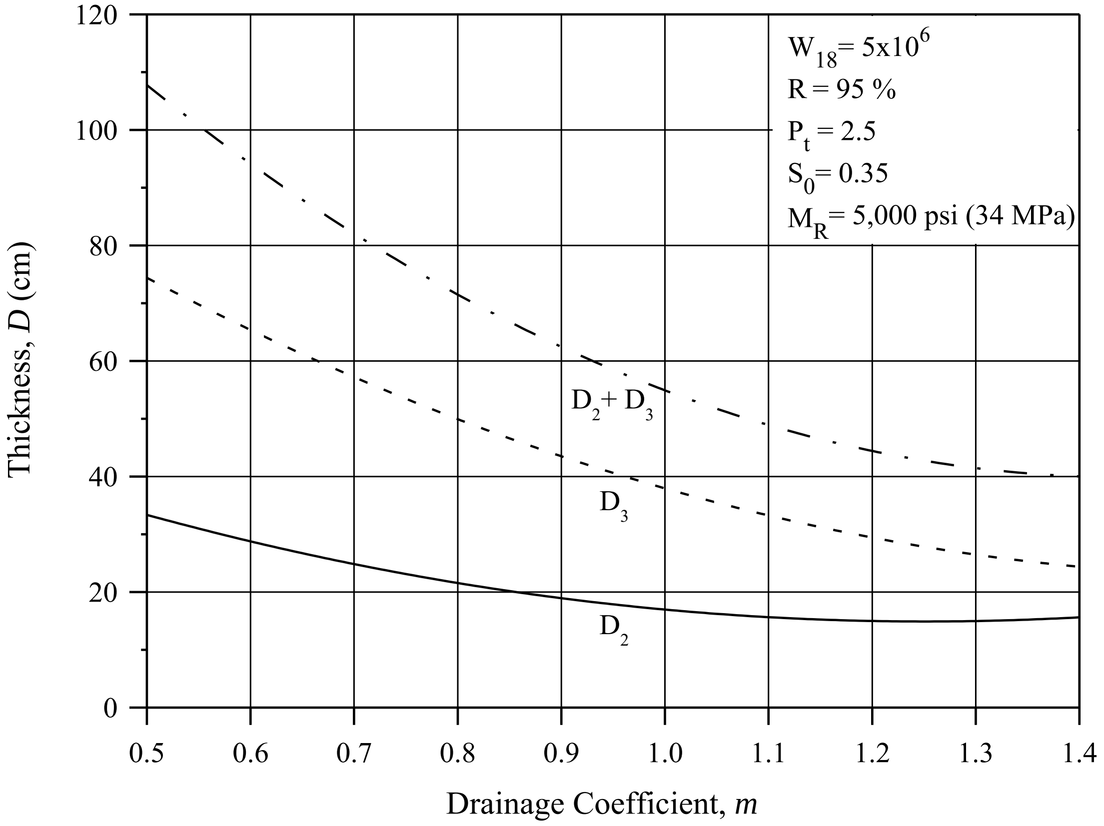

Figure 1 Thickness variation of unbound layers as a function of drainage conditions

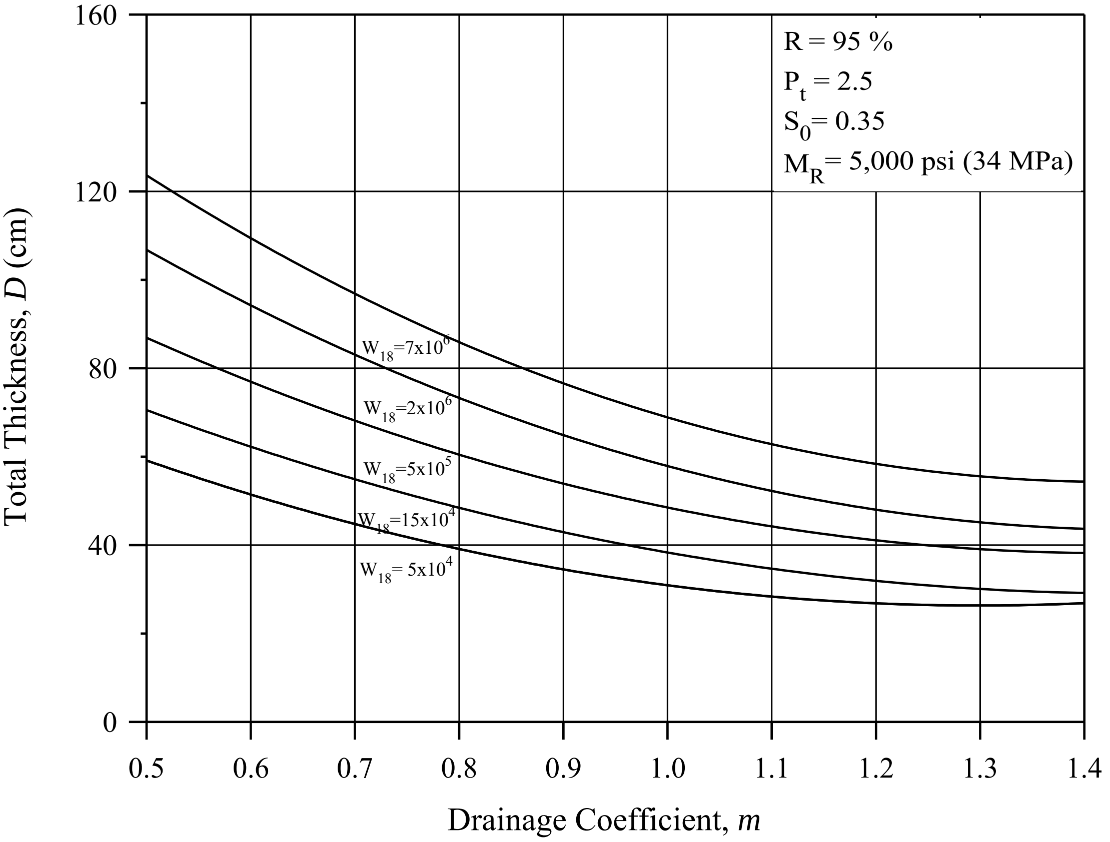

Figure 2 Traffic volume effect on the relationship of drainage coefficient, *m*, and total structural thickness

Keeping the same input data as used in the case of Figure 1, the value of the expected volume was varied between the limiting values in Table 1, namely $5x10^4$, $15x10^4$, $5x10^5$, $2x10^6$ and $7x10^6$ equivalent single axle loads 18 kip (80 kN). The total thickness of the pavement variation as a function of the values of drainage coefficients, m_i, for these different cases is shown in Figure 2. The slope of the curves is similar in all ranges of coefficients *mi*. At the extremely good drainage conditions, the curves are almost parallel to the axis of the coefficients, and only in the case of very high volumes (≥5,000,000 equivalent single axle loads 80 kN) drainage coefficients in the order of 1.3 to 1.4 have a practical significance.

For a traffic volume value W_{18}=5,000,000 and the rest of the input data identical to that of the Figure 1, the effect of the reliability *R* on the relationship of the total thickness of the structure and drainage coefficients *mi* was examined. The extreme values of 50% and 99% have been taken into account as well as rates of 70%, 90% and 95%. Up to *m* value equal to 1.2, the variation is almost linear affected very strongly by the value of Z_R in the basic design equation (Eq. 1), which expresses the reliability level. The results of this correlation are shown in Figure 3.

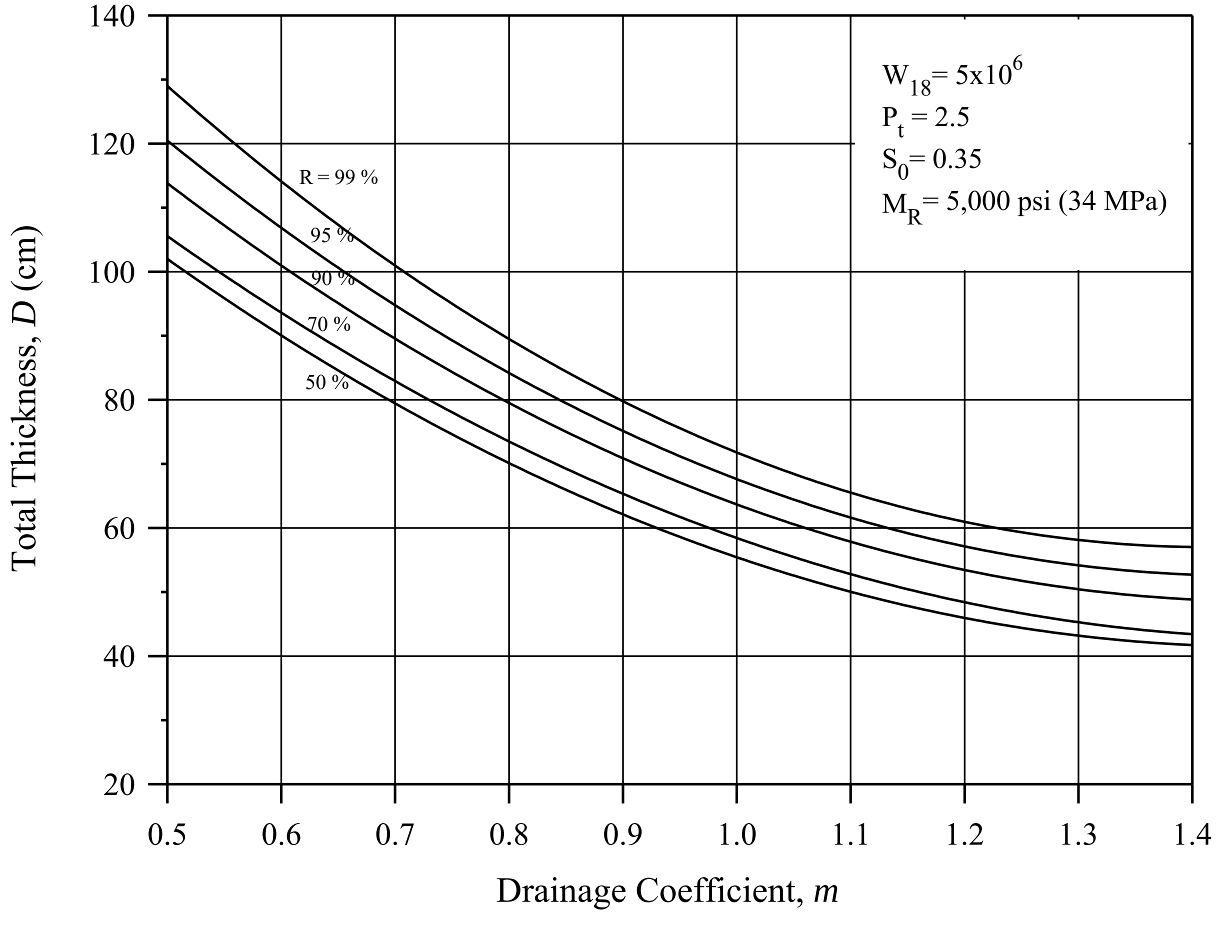

Figure 3 Reliability effect on the relationship of drainage coefficient, *mi*, and total structural thickness

In Table 2, the effect of the standard deviation S_0 (values of 0.30, 0.35, and 0.40) on the base, sub-base and total construction thickness is depicted. The rest input data is the same used in Figure 1. For the particular traffic volume size and other conditions set for this case, the total thickness obtained for S_0=0.35, and Z_R=0.40 is the same because the thickness of the asphalt concrete has been found greater by 0.50 when S_0=0.40 thus reducing the influence of the *mi* of unbound base and sub-base layers. In cases of smaller volumes, higher S_0 value yields an overall thickness increase.

Table 2 Thickness variation of the individual pavement layers

m	S_0=0.30			S_0=0.35			S_0=0.40		
	D_1 (cm)	D_2 (cm)	D_3 (cm)	D_1 (cm)	D_2 (cm)	D_3 (cm)	D_1 (cm)	D_2 (cm)	D_3 (cm)
0.5	12.7	31.8	74.9	12.7	34.3	76.2	14.0	31.8	77.5
0.6	12.7	26.7	62.2	12.7	27.9	64.8	14.0	26.7	64.8
0.7	12.7	22.9	53.3	12.7	24.1	55.9	14.0	22.9	55.9
0.8	12.7	20.3	45.7	12.7	21.6	48.3	14.0	20.3	48.3
0.9	12.7	17.8	41.9	12.7	19.1	43.2	14.0	17.8	43.2
1.0	12.7	15.2	39.4	12.7	17.8	38.1	14.0	15.2	40.6
1.1	12.7	15.2	33.0	12.7	15.2	35.6	14.0	15.2	34.3
1.2	12.7	15.2	27.9	12.7	15.2	30.5	14.0	15.2	29.2
1.3	12.7	15.2	24.1	12.7	15.2	26.7	14.0	15.2	25.4
1.4	12.7	15.2	20.3	12.7	15.2	22.9	14.0	15.2	21.6

CONCLUSION

The dimensioning of flexible pavements consisting of base and sub-base layers made up by unbound aggregates is influenced by the drainage conditions. These have been incorporated in the thickness design equation in the form of drainage coefficients mi. Proper assessment of these coefficients should be based on rainfall height measurements in the area of a highway project and on technical details of devices and arrangements for the free water removal from the pavement granular layers.

The drainage feature in the AASHTO flexible pavement design that needs more research is the pair of drainage coefficients m_2 and m_3 being approached rather empirically. As it has been shown the total thickness, hence the cost, of the structure is significantly affected by the quality of the drainage. Probable underestimation of the mi values is on the side of safety in view of the service time of the construction. However, the construction cost is very high due to the required layer thicknesses, particularly in projects of high value and priority where the expected traffic volumes will be very increased.

As can be seen in Figure 1, the influence of the drainage coefficients is more pronounced in the region of values from 0.5 to 1.0. This can be attributed to the limitations for the minimum base and sub-base thicknesses.

The slope of the total thickness-drainage coefficient curves is similar in all ranges of coefficients mi. At the extremely good drainage conditions, the curves are almost parallel to the axis of the coefficients, and only in the case of very high volumes ($\geq$5,000,000 equivalent single axle loads 18 kip) drainage coefficients in the order of 1.3 to 1.4 have a practical significance.

Empirically based designs used nowadays on a National level may possibly require modifications based on regional experience and on a better assessment of the drainage conditions prevailing in each area crossed by a roadway project. Because design considerations are constantly changed, the necessity for a shift towards more sophisticated design methods is considered obligatory.

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