Assessment of load transfer across transverse joints

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Abstract

The current Austrian pavement design method defines standard pavements for different load classes and construction types. To determine standard rigid pavements a mechanistic model is being used. Traffic load is considered through a standard axle and local climate conditions are only included through different subgrade bearing capacities. Load transfer across transverse joints is taken into account but no relation between the used configurations and geometry of dowels and the effectiveness of load transfer at the joint has been established yet. Within a revision of the Austrian pavement design standards a new multilevel design method will be implemented with the aim to better consider the material characteristics of the used concrete. Furthermore, this model is capable of taking into consideration not only climatic conditions and realistic traffic loading but also boundary conditions like load transfer between adjacent slabs.

Keywords: load transfer; dowel; joint; pavement design; finite element method;

Introduction and background

In order to reduce uncontrollable cracking as a result of shrinkage and thermal stress, plain concrete pavements have to be separated in regular intervals by joints. The Austrian standard construction method for unreinforced concrete slabs requires pavements divided in longitudinal and transverse dummy joints. Thereby the concrete slabs are not separated in their overall thickness, but the young, not yet completely hardened concrete is cut in its top few centimeters. Due to shrinkage cracks propagate from the joint enabling to control the crack. Lateral transfer of forces at the cracks is ensured by aggregate interlock. This means both rough sides of a joint or crack stick into each other and allow the lateral force to be transfered.
Because of weakening aggregate interlock (greater joint or crack widths) the lateral load transfer decreases with increasing service life. Therefore, transverse joints have to be dowelled and longitudinal joints have to be anchored by ty bars even at moderate traffic load. The function of dowel bars consists of load transfer between adjacent slabs, while ty bars are responsible for ensuring the position of the slabs in transvers direction (Houben, 2009).

A major issue raised by under dimensioning of the dowels, in size or number, induces a failure in transferring the lateral force. Another common cause of reduction of the lateral force transfer can be found in weaknesses in the drainage system. Due to failure of joint sealant, surface water can enter and the erosive effects of water lead to the destruction of the concrete

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microstructure and the base of the concrete pavement. In the long term differences in slab elevation across the joint and spalling occur. The consequential damages are not only reduced ride quality but also limited serviceability (Snyder, 2011).

Although, the Austrian standard design method takes load transfer across transverse joints into account, a relation between the used configurations of dowels and the effectiveness of the joints has not been established yet. Whilst research has identified the influence of reduced dowel anchorage lengths and pull-out resistance of dowels (Freudenstein, 2001) in inclined position, improvements to joint load transfer design and analysis are needed (Blab et al., 2012).

The currently used pavement design method has to be seen as critical due to the following reasons:

- The Austrian standard RVS 03.08.63 (FSV 2008) defines standard pavements for different load classes and construction types, which are calculated based on an analytical design method.
- In this design method a standard concrete with defined stiffness and fatigue behavior is being used.
- Traffic load is only considered through a standard axle, whilst traffic and axle load distribution are not considered.
- Climatic conditions are only included through different subgrade bearing capacities.
- A relation between the used configurations of dowels and the effectiveness of the joints is missing.

Based on these considerations a revision of the design method for unreinforced concrete pavements was conducted.

This paper describes:

- the development of a dowel and a joint effectiveness number
- an in-depth parameter study on impacts of different friction coefficients and dowel
- the effect of the dowel distances on the joint effectiveness number.

Methods

For the presented study different finite element models, using the software ABAQUS (SIMULIA 6.14-1) were developed. To describe the potential of load transfer across transverse joints, a dowel and a joint effectiveness number were implemented.

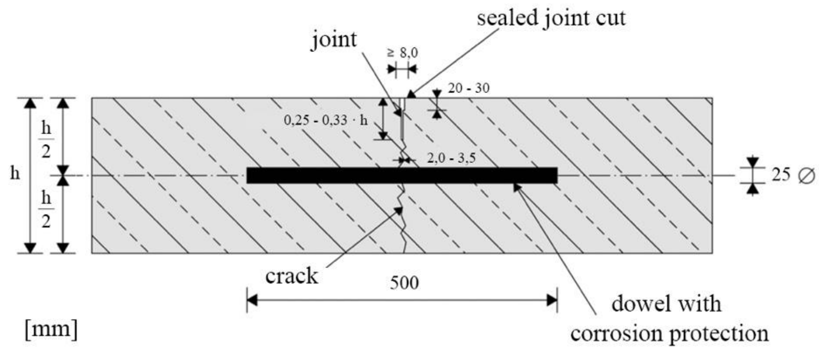

Figure 1 Construction of a contraction joint according to RVS 08.17.04 (FSV 2013)

Construction of transverse contraction joints. According to the Austrian standard RVS 08.17.04 (FSV, 2013) doweled transverse contraction joints have to be 2,0 mm to 3,5 mm wide and between 0,25 · h deep (with h = thickness of the concrete slab). To maintain better load transfer, dowel bars are applied at mid-height of the concrete slab. The standard dowel used in Austria has a diameter Ø of 25 mm (or about 10% of the concrete slab thickness) and a length of 500 mm. To protect the dowels against environmental influences they are either coated with a corrosion protection or surrounded by a layer of plastic coating. Figure 1 shows the construction of a transverse contraction joint with a standard dowel.

Definition of the dowel effectiveness number. Using the finite element method, enables to simulate realistic situations with respect to traffic load, geometry of the concrete slab and the dowel, material characteristics and interactions between the various layers as well as the concrete and the dowel bars. To evaluate the load transfer potential of a dowel, a so called dowel effectiveness number, DEN, is introduced, which is equal to the equivalent stiffness of a vertical spring. In order to obtain DEN, an applied load F in a system according to Figure 3 has to be divided by the resulting vertical deflection w, as shown in the equation below and in Figure 2.

$$\mathrm{DEN} = \frac{\mathrm{F}}{\mathrm{w}} \; [N/mm] \qquad (1)$$

with

DEN … dowel effectiveness number [N/mm]

F … single wheel load [N]

w … vertical deflection [mm]

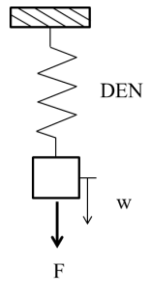

Figure 2 Definition of the dowel effectiveness number

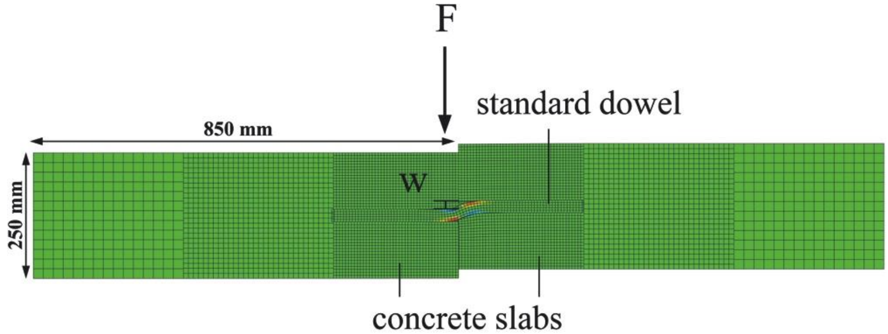

Figure 3 Section of 3D finite element model to calculate DEN

The size of the dowel effectiveness number depends on the following parameters:

- friction coefficient between dowel and surrounding concrete
- dowel diameter
- dowel stiffness
- anchorage length of the dowel

In depth parameter studies were used to evaluate the impact of these parameters (see section Discussion and results). Only the modulus of elasticity of the dowel was kept constant with $E_s = 210\ 000\ N/mm^2$ (steel). The used 3D finite element model (see Figure 3) consists of two adjacent concrete slabs, which transfer the later force through aggregate interlock and dowel bars to the adjacent slab. To analyze the potential of load transfer across transverse constraint joints, only a small part of two slabs (l/w/h = 850/700/250 mm) were consciously chosen. The two slabs were separated by a joint and connected by a dowel to transfer the lateral force. The friction along the joint to simulate aggregate interlock was first defined as μ = 0,6 and later reduced to μ = 0,01 to consider the load transfer through dowel bars separately. While the unloaded slab was fixed in its vertical and horizontal displacements (x-, y-, and z- direction), displacements along the vertical axis (y-direction) of the loaded slab were enabled.

Development of the joint effectiveness number. The Westergaard's theory distinguishes three different loading conditions due to a single wheel load, located in the middle, along the edge or in the corner of a single concrete slab. Closed formulas for maximum vertical displacement and stresses in the slab are available for these three load cases. According to Westergaard (Eisenmann and Leykauf, 2003) the displacement along the edge of the slab is 3,46 times higher than in its middle. To estimate the displacement of a transverse joint besides the effect of aggregate interlock, the provided number of dowels has to be taken into consideration. Through the combination of both slabs, lateral forces of the loaded slab are transfered to the unloaded slab and consequently the displacement of the transverse joint is reduced. The efficiency W (equal to the American Concrete Pavement Association's Joint Effectiveness index) of the joint arises from the displacement of the loaded joint edge y_1 and the displacement of the unloaded joint edge y_2 and can be calculated with the following equation:

$$W = \frac{2 \cdot y_2}{y_1 + y_2} \cdot 100\ [\%] \tag{2}$$

with

$$y_1 = 3{,}46 \cdot \frac{F}{8 \cdot k \cdot l^2}\ [mm] \tag{3}$$

$$l = \left(\frac{E \cdot h^3}{12 \cdot (1-\mu^2) \cdot k}\right)^{0,25}\ [mm] \tag{4}$$

and

W … efficiency index of the joint [%]

y_1 … displacement of the loaded joint edge [mm]

y_2 … displacement of the unloaded joint edge [mm]

F … single wheel load [N]

k … modulus of subgrade [N/mm^3]

l … elastic length [mm]

E … modulus of elasticity of concrete [N/mm^2]

h … thickness of concrete slab [mm]

μ … Poisson's ratio of concrete [-]

The potential of load transfer across transverse joints is about 50% of the efficiency index of the joint. An efficiency index of 100% implies a total load transfer across transverse joints, at which the displacement of the loaded and unloaded joint edge are identical. At an efficiency index of 0% no load transfer exists, the lateral forces cannot be transferred to the adjacent slab and the displacement of the unloaded joint edge is equal to zero. According to (Eisenmann and Leykauf, 2003) doweled joints may have an efficiency index of minimum 80% even after 30 years of traffic load.

Based on Westergaard's efficiency index a joint effectiveness number, JEN, was introduced to evaluate the load transfer efficiency of transverse joints by taking the dowel efficiency (through the aforementioned dowel effectiveness number DEN) into account. JEN is defined as the relation between the shear stresses at the edge of the loaded and unloaded slab.

$$JEN = \frac{\tau_{loaded}}{\tau_{unloaded}} \qquad (5)$$

with

JEN … joint effectiveness number [-]

τ_{loaded} … shear stress along the loaded joint edge [N/mm^2]

$\tau_{unloaded}$ … shear stress along the unloaded joint edge [N/mm^2]

In another finite element model shown in Figure 4, consisting of two adjacent slabs (l/w/h = 5500/5500/250 mm), which are supported on an elastic foundation, the dowels were replaced by vertical springs with stiffness equal to DEN. The results of this analysis are the maximum displacement of the loaded and unloaded slab. Furthermore, stress and lateral force at a defined load can be determined along the joint.

This method can also be used to evaluate existing joints using Falling Weight Deflectometer (FWD) tests. The FWD simulates the passage of a vehicle by a dynamic loading through a load plate and measures the resulting deflection on each side of the pavement joint (Snyder, 2011). As the FWD is one of the most common ways to evaluate joint load transfer efficiency, an evaluation using the joint effectiveness number can be a useful addition to analyze the condition of existing joints.

Discussion and results

Impact of friction coefficient. To estimate the relation between the equivalent stiffness (DEN) of a standard dowel (Ø 25 mm, length 500 mm) and the friction coefficient between the dowel and concrete, the friction coefficient was varied. To eliminate the influence of aggregate interlock the friction along the joint was defined as μ = 0,01. The results of the finite element analysis show a linear relation between friction coefficient and DEN. With increasing size of the friction coefficient, the number of equivalent stiffness is also growing (see Figure 5). Although load transfer increases with rising friction coefficient, a friction coefficient of 0,2 can be assumed as realistic. Furthermore the lower the friction coefficient between the dowel and the concrete, the better thermal stresses can be relieved due to possible dowel movement. In the further calculations a friction coefficient of 0,01 was considered to eliminate the influence of the friction between the dowel and the surrounding concrete for further analyses.

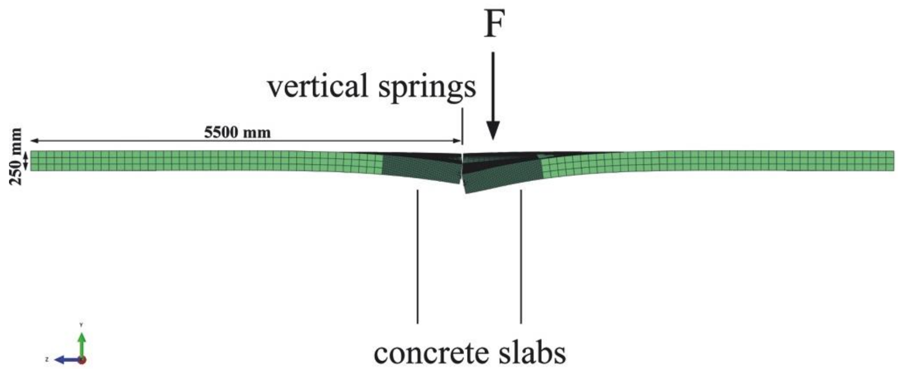

Figure 4 Section of 3D finite element model to calculate JEN

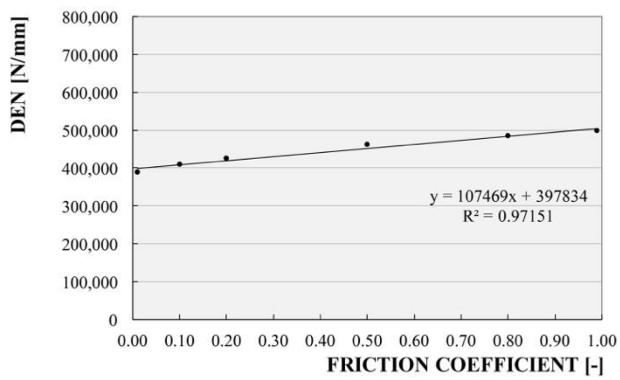

Figure 5 Impact of the friction coefficient on DEN

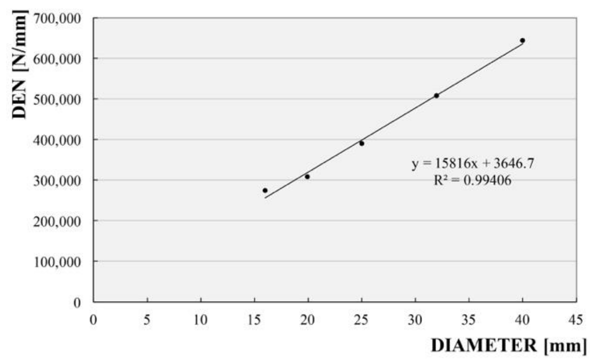

Figure 6 Dowel effectiveness number as a function of the dowels diameters

Impact of dowels diameters on DEN. Additionally, to the standard dowel many companies offer a variety of dowel models. Hence, different dowel configurations (diameter and length) are analyzed and compared. To estimate the relation between the equivalent stiffness (DEN) and the diameter of the dowel, a dowel with a length of 500 mm was varied in the most commonly used diameters. The dowel effectiveness number was calculated for the diameters 16, 20, 25, 32 and 40 mm used in 250 mm thick concrete slabs. The results can be seen in Figure 6. Using this design diagram, a simple and straight forward method for choosing the adequate dowel in consideration of the thickness of the concrete slabs is presented. In case of very small dowel diameters transvers stresses higher than the allowed concrete strength may occur at the top side of the dowel.

Impact of anchorage length on DEN. The results from this study agree with prior research on the influence of reduced dowel anchorage lengths on the efficiency of joint construction of concrete pavements (Freudenstein, 2001). Dowel anchorage lengths greater than 100 mm have no influence on the load transfer efficiency, but dowel anchorage lengths lower than 100 mm may induce significant increases in their relative displacements and stresses. Figure 7 shows that equivalent stiffness decreases with reduced dowel anchorage length.

Impact of dowel distances on JEN. Not only different dowel diameters, but also the spacing between the used dowels has an influence on the effective load transfer across transverse contraction joints. To identify this influence, the distances between the dowels were varied and the dowel effectiveness number of a standard dowel (Ø 25 mm, length 500 mm) was used. The efficiency index of the joint W according to Westergaard's theory (see equation (2)) for the dowel distances of 200, 300, 400, 500 and 600 mm were calculated. As presented in Figure 8 the greater the distance the higher the relative displacement Δu_{max} below the load of the adjacent slabs and the lower the joint efficiency index (Figure 9). The displacement along the joint edge for dowel spacing of 300 mm is shown exemplarily in Figure 10.

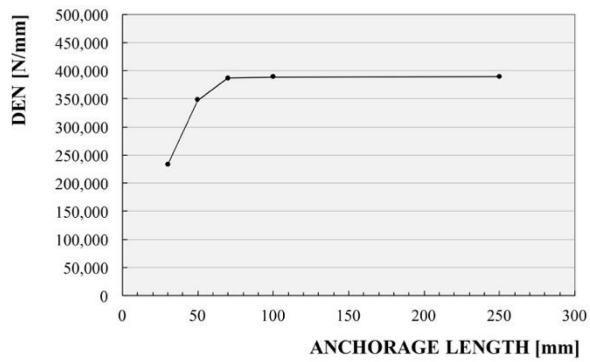

Figure 7 DEN depending on the anchorage length

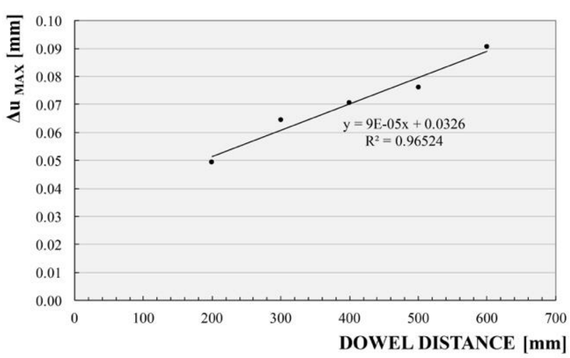

Figure 8 Relative displacement depending on the dowel distances

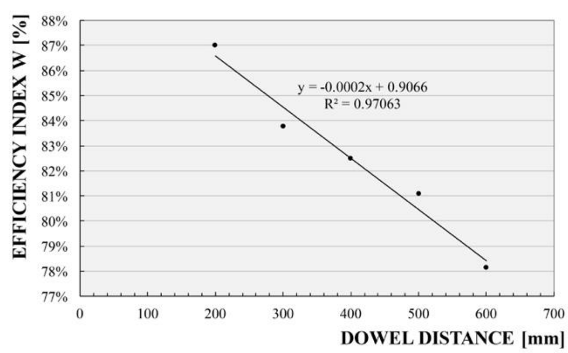

Figure 9 Efficiency index of joints depending on the dowel distances

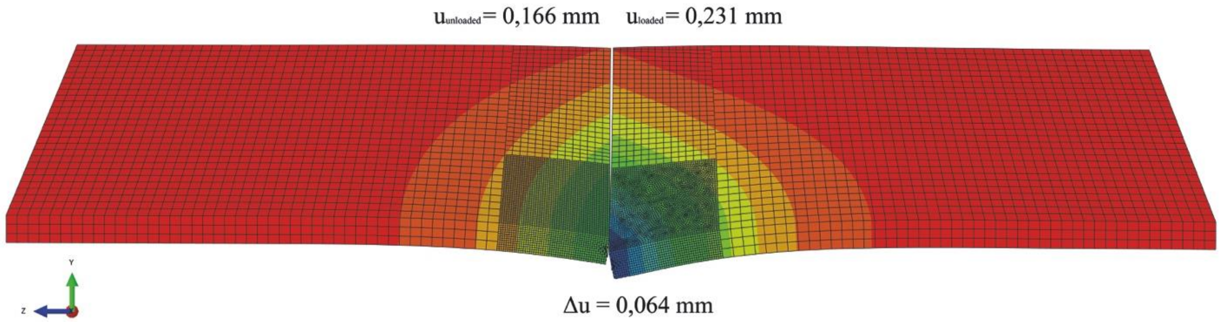

Figure 10 Displacement along the joint edge for dowel spacing of 300 mm, F=50kN and k=0,1 calculated with ABAQUS

To estimate the joint effectiveness number JEN the shear stresses $\tau_{unloaded}$ and τ_{loaded} were compared. The results are presented in Figure 11 and Figure 12. Figure 11 shows the relative shear stress $\Delta\tau = \tau_{loaded} - \tau_{unloaded}$ for various dowel distances. It can be assumed that with decreasing dowel distances, shear stresses and deflections decrease. Furthermore, the joint efficiency index W increases with greater dowel spacing. The newly introduced joint effectiveness number, however, decreases with greater dowel distance (see Figure 12). Thus it appears that a reduction of dowel spacing can be an effective way to reduce the relative shear stress as well as deflections.

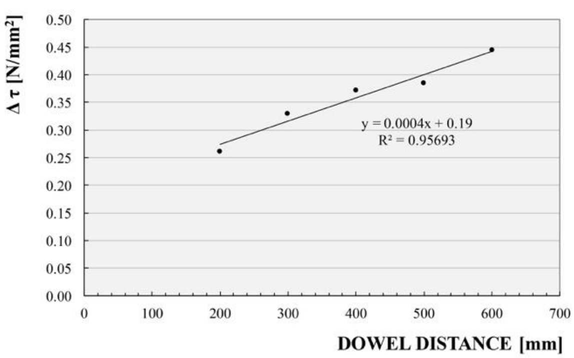

Figure 11 Relative shear stress depending on the dowel distances

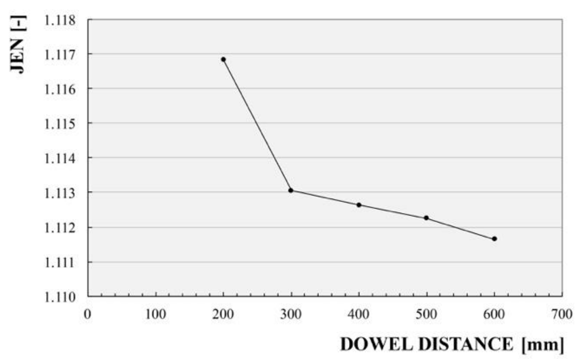

Figure 12 Joint effectiveness number JEN depending on the dowel distance

Conclusion

The main motivation for the research project presented within this paper was to develop an efficient and simple method to consider various dowel and joint configurations in the pavement design process and to give awarding authorities, pavement designers and paving companies the opportunity to develop and evaluate innovative rigid pavement constructions.

To achieve these objectives an in-depth parameter study using Finite Element simulations, including variations of dowel diameter, friction coefficient between dowel and concrete and dowel anchorage length, was carried out.

It was proven that the dowel bar diameter strongly effects the load transfer efficiency and, thus, the pavement performance. Therefor, a dowel effectiveness number (DEN) was introduced to evaluate the dowel's load transfer potential. It has been demonstrated that a linear relation between different diameters and the equivalent stiffness (DEN) exists. Greater dowel diameters cause increased dowel stiffness and reduced deflections as well as shear stresses along the joint. Thereby joint faulting and pumping decrease while ride quality increases.

Furthermore, it could be shown, that DEN increases linearly with increasing friction coefficients between the dowel and the surrounding concrete. As follows from the results, a friction coefficient μ= 0,2 can be assumed as realistic.

According to (Freudenstein, 2001), the dowel length should be selected in consideration of sufficient anchorage length on both sides of the joint and of dowel placement across the joint. Furthermore, anchorage lengths lower than 100 mm may induce significant increases in their relative displacements and stresses. These results could be confirmed in this work.

Additionally, the influence of dowel spacing, previously analyzed by (Snyder, 2011) was verified in this study. Thereby, not only a joint efficiency index W (based on displacements along the joint according to Westergaard's theory) was considered. Additionally, a joint effectiveness number (JEN) was introduced, which relates shear stresses along the joint in the loaded and unloaded slab. Furthermore, Falling Weight Deflectometer (FWD) tests results can be used to assess JEN and analyze the condition of existing joints.

With these results at hand a simple and straight forward method for choosing the adequate dowel configuration for concrete pavements is presented. The presented results will be implemented in a new mechanistic design approach.

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