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# An Overview of Moisture Damage in Asphalt Mixtures

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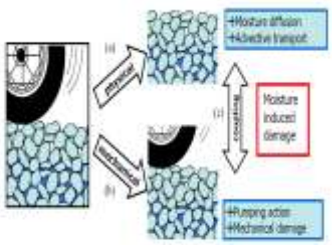
**Graphical abstract**




**Abstract**

This paper presents a short review on moisture induced damage in asphalt mixtures. Moisture induced damage is one of the most common causes of pavement distress that results in loss of strength, stripping, raveling, fatigue damage and permanent deformation. Different mechanisms have been used to explain the process of moisture damage in asphalt pavements. However, the moisture damage mechanism takes place due to the interaction of several different processes. The applicability of a single test method to evaluate moisture damage is impractical to a wide range of materials and conditions. Therefore, a new laboratory based testing procedure and analysis protocol is required, with the aim to simultaneously consider the effects of both traffic impact and moisture damage. The proper material design, efficient construction methods, reliable laboratory techniques and well planned highway surface and subsurface drainage systems may lead towards a sustainable asphalt pavement that is sufficiently durable to resist moisture damage. Although considerable advances concerning the subject have been reported, yet there is still a need to address certain issues that are actually involved in the process of asphalt mixture moisture susceptibility.

*Keywords*: Moisture damage, pavement distress, stripping, surface energy, warm mix asphalt



## 1.0 INTRODUCTION

Asphalt pavement failure modes are normally classified as stability (load) or durability related failures. Stability-related failure modes are linked with problems in asphalt mixture design and displacement in Hot Mix Asphalt (HMA) mix under normal loading, while durability-related failure modes are linked with pavement age and weather conditions [1]. Moisture damage is identified as the loss of strength or durability in an asphalt pavement due to the effects of moisture and may be evaluated based on the loss of mechanical properties in asphalt mixtures [2].

In asphalt mixtures, the binder serves to hold the aggregates firmly and act as a sealant against moisture ingress [3]. The HMA may be sensitive to the presence of water in the finished pavement [4]. Santucci [5] described many sources that can lead to the existence of water in the pavement and its presence is inevitable. Water can penetrate via cracks on the surface of the pavement, via the interconnectivity of the air voids system or cracks, due to rising ground water level, or from the road shoulders. The permeability of asphalt mixtures is directly proportional to the air voids within mixture. Asphalt mixtures with high porosity will provide a pathway for the entrance of damaging air and water [6]. During the mixing process, the insufficiently dried aggregates may lead to the presence of trapped moisture in the coated aggregates [7].

Moisture damage has remained a major concern among asphalt pavement technologists for many years [8]. Since 1920's, researchers have been looking for a test that can differentiate between good and poor performing asphalt mixtures in terms of stripping potential. It has been known that the problem relates to the loss of adhesion between asphalt and aggregate and the loss of cohesion within the asphalt binder. The challenge that still remains is to identify test procedures that can well predict mixture moisture susceptibility [8].

According to Kim et al. [9], most of the recognized and severe forms of pavement distresses like stripping, raveling, fatigue damage, and permanent deformation results in premature pavement failure which is related to moisture damage. In other words, intrusion of moisture into the pavement structure decreases its strength and advances in one or more of the visible form of the above stated distress. Numerous efforts have been made to classify moisture damage mechanism in asphalt mixtures, so as to evaluate and develop new test methods. The filler used in asphalt mix is prolonging the lifespan on the pavement and increasing its resistance against water penetration [10]. During asphalt mix design, the use of anti-stripping agent is essential to prevent moisture damage. Hydrated lime and polymers are commonly used to mitigate stripping in asphalt mixtures. As a result, it reduces the hydrophilic properties of the aggregate and changes the predominant electrical charges at the aggregate surface [11].

Moisture damage mechanism in asphalt pavements is a complex phenomenon and depends on numerous factors that yet are needed to be addressed. These include:

(i) Factors affecting moisture damage in the field,
(ii) Laboratory testing for prediction of moisture damage, and
(iii) Efficiency of various treatments to mitigate moisture damage.

## ■2.0 LABORATORY APPROACHES FOR EVALUATION OF MOISTURE DAMAGE IN ASPHALT MIXTURES

One of the major concerns related to HMA deformation is moisture-induced damage [12]. Many attempts have been made by asphalt technologists to develop a test procedure that is reliable and useful to evaluate moisture damage. The development and classification of a test procedure that truly simulates field conditions is an important consideration during the standardization process of moisture damage testing procedures. Some tests have been calibrated and applied on a local basis. None of the test has been successfully regulated and implemented across a wide range of conditions. This is due to the lack of actual consideration of field conditions in the laboratory, problem with the repeatability, difficulty in operating test procedures and lack of method that truly represents the actual mechanisms of moisture damage.

Moisture susceptibility tests on asphalt–aggregate mixture are carried out either on loose or compacted mixes. Test conducted on loose mixtures include static immersion and boiling water test. These two were among the first introduced to the paving industry [8]. This was followed by the immersion-compression test in late 1940s. The test was the first to become an ASTM standard conducted on compacted specimens in the mid-1950s. To evaluate asphalt moisture damage, investigations made in 1960's brought substantial awareness in asphalt paving industry for the inclusion of considerable influence of traffic and environmental impact. The work of researchers such as Johnson [13], Schmidt [14], Jimenez [15] and Lottman [16] highlight the importance of these factors [8].

Solaimanian et al. [8] stated that during the past few decades, the performance of HMA in the presence of water is a complex issue and has been the subject of numerous studies. Asphalt scientists and state highway agencies have been continuously investigating suitable laboratory test procedures that can simulate and forecast asphalt pavements moisture damage in the field. Since 1920s researchers have been well aware that asphalt and aggregate adhesion bond becomes weaker in the presence of water called stripping and the cohesion failure is described as the deterioration within binder. Early studies on asphalt mixtures to simulate moisture damage were carried out by Nicholson [17], Riedel and Weber [18], McLeod [19], Hubbard [20], Powers [21], Winterkorn et al. [22], Saville and Axon [23], Winterkorn [24-26], Krchma and Nevitt [27], Krchma and Loomis [28], and Hveem [29], among others. A widespread bibliography covering work performed prior to 1959 is given by Rice [30].

According to Solaimanian et al. [8] tests that have been developed for evaluating asphalt moisture damage can be generally categorized into qualitative and quantitative.

Qualitative tests provide a subjective evaluation of the stripping potential and include the followings:

(i) Boiling water test
(ii) Freeze–thaw pedestal test
(iii) Quick bottle test
(iv) Rolling bottle method

The quantitative tests provide a value for a specific parameter such as strength before and after conditioning. These tests include the followings:

(i) Immersion–compression test
(ii) Indirect tensile test
(iii) Marshall Immersion test
(iv) Double punch method
(v) Resilient modulus tests
(vi) Hamburg wheel tracking
(vii) Dynamic Modulus and many others.

It is important to mention that a single test method for evaluating moisture induced damage is often impractical due to a wide range of material properties and conditions. Hence, a newly laboratory-based testing procedure along with analysis protocol needs to be developed for the evaluation of moisture damage that could consider the simultaneous effects of traffic impact load in the presence of moisture.

## ■3.0 MECHANISM INVOLVED IN ASPHALT MOISTURE DAMAGE

Terrel and Shute [31] explained four theories (a) chemical reaction, (b) surface energy, (c) molecular orientation, and (d) mechanical adhesion that describe the adhesion of asphalt and aggregate. Terrel and Swailmi [32] pointed out that water can influence cohesion in several ways, including weakening of the mastic due to moisture saturation and void swelling or expansion. The main causes of distress occurring in asphalt pavements are bonding failure between the asphalt binder and the aggregate surface [33]. According to Brown et al. [34], Moisture damage can take place due to three main reasons:

(i) Loss of cohesion of the asphalt film,
(ii) Failure of the adhesion between the aggregate particles and the asphalt film,
(iii) Degradation of aggregate particles due to freezing.

Traditionally, six contributing mechanisms of moisture damage have been identified: detachment, displacement, spontaneous emulsification, pore pressure–induced damage, hydraulic scour, and the environmental effects on the aggregate–asphalt system. However, it is evident that moisture damage is a combination of processes rather than one mechanism. The understanding of moisture damage process becomes more important by taking into account the micro mechanisms that affect the adhesion at asphalt aggregate interface and cohesion strength and durability of mastic [2]

Damage in asphalt mixtures can appear within the mastic (cohesive fracture) or at the aggregate–mastic interface (adhesive fracture or failure). The failure type whether cohesive or adhesive in asphalt mixtures depends on the nature of the mastic and the relative thickness of the mastic around the coarse and fine aggregate [35]. Another damage process identified by Kringos [36] is the combined effects of traffic loading on wet asphaltic mix. The macro–pores in saturated asphalt pavement create an intense water pressure field in these pores due to traffic loading. The excess pore pressures are also formed away from the actual wheel path, due to which the water has no time to reallocate itself within the mix.

Kringos [36] also summarized and divided the moisture damage into physical and mechanical processes as shown in Figure 1. The physical damage is an important contributor, where molecular diffusion of moisture and a 'washing away' process of mastics takes place due to the action of fast water flow. The mechanical damage process that contributes to moisture damage is the occurrence of severe water pressure fields inside the mix due to traffic loading and referred as 'pumping action'.

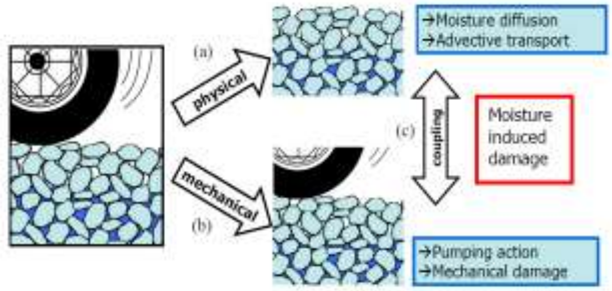



**Figure 1** Schematic of new approach towards moisture induced damage [36]

The micro mechanism of asphalt aggregate interaction along with physical and mechanical damage processes should be investigated. Thus, the component surface chemistry that prevents the damage in asphalt mixture due to moisture coupled with traffic loading can be explored properly.

## ■4.0 ASPHALT PAVEMENT MOISTURE INDUCED DAMAGE

In the Distress Identification Manual for the Long-Term Pavement Performance Project (LTPP), each distress is grouped into one of the following categories [37]:

(i) Cracking
(ii) Potholes
(iii) Surface deformation
(iv) Surface defects and
(v) Miscellaneous distress

Copeland [38] described that asphalt moisture induced damage may result in cracking, permanent deformation, raveling (loss of surface material), and localized failures (potholes). The understanding of various pavement distress types is essential to categorize the causes of failure. Copeland [38] also highlighted that moisture damage in asphalt pavement is a primary distress mode that accelerates the degradation and failure of the mixture in parallel with distresses in each of the above mentioned categories. Adhesive bond at asphalt-aggregate interface degrades in the presence of moisture and can lead to cracking under applied loading due to tensile stresses. Finally, these cracks in the pavement provide opportunity for moisture to enter into the asphalt mixture. Moisture can also influence the cohesive bond within asphalt mastic and weakens the asphalt binder leading to permanent deformation.

Stripping is fundamentally the loss of bond between the asphalt and aggregate [39]. The stripping of aggregate can occur due to the continuous action of moisture and traffic load. Thus, the early form of stripping grows up more rapidly, causing dislodgement of aggregate which eventually leads to the formation of pothole as shown in Figure 2 [36].

a) raveling b) potholing

**Figure 2** Moisture induced damage in asphalt mixture [36]

Several methods are introduced to protect pavements from possible moisture damage which includes the pavement surface and subsurface drainage system. Efficient construction techniques are to be employed that truly reflects the design parameters used in the laboratory investigations.

## ■5.0 SIGNIFICANCE OF MOISTURE DAMAGE AS A DESIGN PARAMETER

Pavements are subjected to different types of stresses during their design life. A well designed pavement can adequately performs its function during the entire design life, and any form of distress is kept within allowable limits. The expected performance with appropriate economic considerations is only possible when the pavement design includes moisture damage evaluation as a design parameter [40].

The Modified Lottman test (AASHTO T283) is a standard test that is used to evaluate moisture susceptibility of asphalt mixtures. The Marshall mix design method includes the American Association of State Highway and Transportation Officials (AASHTO) T283 [41] test procedure for moisture damage evaluation and with the development of the Superpave mix design methodology, the same test method was used with the modification of the compaction method. Moreover, AASHTO T283 [41] assists in reducing the problem but it does not appear to be a very useful indicator of stripping [34].

The usefulness of AASHTO T 283 and its compatibility with the Superpave® volumetric mixture design system is mentioned in an NCHRP Project 9-13 report [42]. Improvements to the conditioning procedures were suggested by [42] which resulted in the current standardized version of AASHTO T 283. Therefore, in NCHRP Project 9-13, AASHTO T 283 still remains the most useful test method to predict moisture sensitivity before construction as compared with other available procedures. However, this test is empirical in nature and is liable to give either false positive or false negative results for the prediction of moisture susceptibility. Therefore, to predict moisture susceptibility with confidence, there are still concerns regarding its ability to assess [7]. Since AASHTO T283 [41] is used as the standard test method for many years, it assists in minimizing the problem by identifying some of the mixes susceptible to moisture damage. Moreover, it does not appear to be a very precise indicator of stripping. The dynamic modulus and flow number tests have been practiced in replacement of indirect tensile strength test to take advantage of performance evaluation within a pavement structure in mechanistic pavement design [43]. The use of ultrasonic technique to improve the testing and evaluation of asphalt mixture and dynamic modulus test in the indirect tensile test (IDT) mode was also attempted by Van et al. who presented the theoretical demonstration of how ultrasonic measurements could be used to calculate complex moduli [44]. The dynamic modulus, dynamic shear modulus, and phase angle master curves were constructed using the time-temperature superposition principle. Ultrasonic longitudinal- and shear-wave data was collected on the same specimens. This enhances the use nondestructive testing techniques in asphalt mixture studies. Cheng et al. [45] used Ultrasonic Detection Method (UDM) to determine the ultrasonic velocity of asphalt mixtures at different temperatures and water contents during the cycles of Water-Temperature-Radiations (W-T-R). Cheng et al. [45] reported that UDM can be used to quickly evaluate the damage state of asphalt mixture after the action of W-T-R cycles and it also effectively predicts the damage degree.

In Figure 3, the flow chart indicates the implementation of Mechanistic Empirical Pavement Design Guide (M-E PDG) software in which all of the steps provided in Figure 3, are performed automatically, excluding pavement structure and material selection. The predicted performance of trial design is evaluated against specified reliability level.

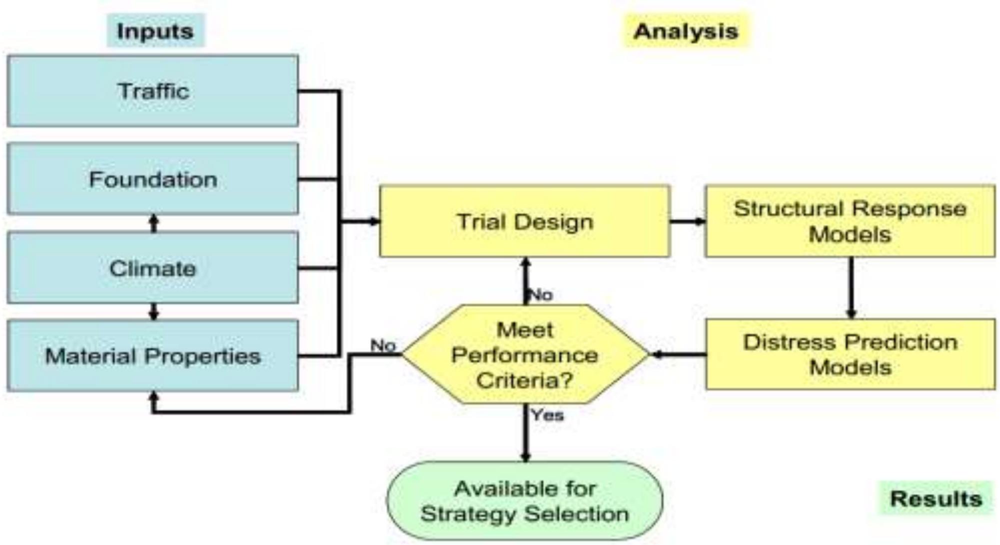



**Figure 3** M-E flexible pavement design flow chart [46]

A trial design is checked for performance criteria. If suppose it does not meet the criteria then the thicknesses or materials selection must be modified until it is accepted. It is necessary to highlight the importance of moisture susceptibility of asphalt mixture during distress prediction models stage, so that materials behavior will provide a response indicator to moisture damage. Hence, the proper modifications during the design process can produce a material that is more moisture resistant [46].

The main objective of moisture damage-related research is to improve serviceability of flexible pavements. The pavement structure's strength is considered as an indicator to measure its serviceability. However, it is not easy to quantify the structural strength of a structure precisely but it is more difficult to quantify moisture damage effects on asphalt mixture strength. A framework proposed by Copeland [38] identifies four major areas of research:

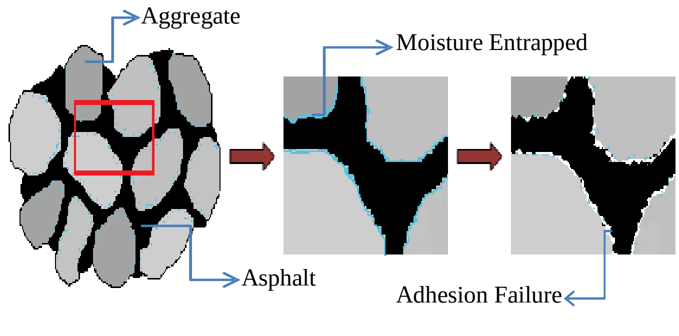
(a) Determination of the primary (most influential) mechanisms that contribute to moisture damage
(b) Study of the component materials and their behavior in dry and moisture conditions
(c) Development, validation, and verification of response predictions
(d) Adequacy of the design procedure to address moisture induced damage in asphalt mixtures

The use of only one test procedure for the classification of moisture susceptible mixture may be difficult if it is not impractical, as most researchers agree that moisture damage based on only one test method cannot predict mixture moisture susceptibility precisely. A combination of more than one method may be selected as material selection criteria in pavement design methodology.

## 6.0 MOISTURE DAMAGE AND WARM MIX ASPHALT

Recently, Warm Mix Asphalt (WMA) technology was developed that allows asphalt mixture to be placed at lower temperatures compared with conventional mixture. This technology is rapidly gaining acceptance due to its sustainability compared with HMA. The objective of WMA is to allow the use of existing HMA plants, standards and specifications so that it has similar qualities as HMA [47]. The main issue related with moisture susceptibility of WMA mixtures is the effect of WMA additives on the adhesion between asphalt and aggregate [48, 49]. Further, some foaming technologies introduce water and the effects of incomplete aggregate drying at low temperature during WMA production process may influence the moisture susceptibility of asphalt mixtures [50].

According to the National Center for Asphalt Technology (NCAT) [51, 52], as the mixing temperatures are reduced the mixes showed increased affinities towards rutting and moisture susceptibility. This is due to the aggregates not properly dried and less aging taking place during mixing at low temperature. Figure 4(a), (b), (c) shows the schematic diagram of moisture entrapment at asphalt aggregate interface during WMA production.




a) Asphalt mixture b) Binder aggregate interface c) Damaged interface

**Figure 4** Moisture damage in warm mix asphalt holding moist aggregates

According to D'Angelo et al. [53], WMA production temperature can range from 20 to 55°C lower than typical HMA. There are many benefits that promote the implementation of WMA but the primary benefit is the lower mixing and compaction temperatures which can lead to environmental preservation and energy savings. Kanitpong and Likitlersuang [54] suggested that further investigation is required to evaluate the performance and durability of WMA, particularly ITS moisture susceptibility. The WMA reduction in mixing temperature could adversely affect ITS moisture sensitivity due to the entrapment of moisture in the aggregate particles or due to the inferior coating because of binder high viscosity. Both factors may lead to higher probability of stripping to occur, hence, mixture moisture related damages. On the other hand, warm mix additives such as surfactants form a bridging effect between the asphalt binder and the aggregate surface, enhancing adhesion and resist the action of water. This is normally done due to the polarized extremities of additive molecules with opposite charges that attract other material, allowing them to bind with the aggregate. The adhesion promoters reduce the surface tension at the binder-aggregate interface therefore; can also coat the surface areas of large amounts of fine aggregates or dusts.

Moisture damage in asphalt mixtures is a long term phenomenon that appears during the design life of a pavement. Therefore, it is quite essential for pavement technologist to identify the damaging process in WMA mixtures. Also the WMA supplier should take into consideration the right balance between lowering the mixing temperature using adequate amount of anti-stripping agents and adequately drying the aggregates used in mixes.

## 7.0 FUTURE WORK

There are drawbacks in many moisture sensitivity test methods on asphalt mixtures. This includes the subjective nature of the qualitative test methods which are based on individual visual assessments [55]. The latest research advancements are focused on studying the micro and macro-mechanisms of moisture damage in asphalt mixtures. Based on molecular scale, the asphalt aggregate interface adhesion and cohesion within asphalt are explained by mechanical, chemical reaction, molecular orientation, surface energy and weak bound theories. In addition, there are mechanical theories that explain the adhesion and cohesion failure of asphalt mixtures on a macro-scale [56]. Mehrara and Khodaii [56] concluded that macro-mechanisms of moisture damage are in fact a combination of effects of physical solicitations such as stress caused by traffic and thermal loading and water entrance to pavement structure. The use of nano-materials such as nano-clay, nano-silica, nano-hydrated lime, nano-sized plastic powders, or polymerised powders, nano-fibers, and nano-tubes are promising and creative techniques in the material industry to prevent moisture damage [57].

The lack of fundamental understanding of the mechanism by which the presence of moisture in an asphalt mixture leads to damage is a major challenge [58]. Surface free energies are the important properties of any substance when they are mixed with another substance. Asphalt mixture is mainly constituted by bitumen and aggregate particles. The purpose of bitumen is to glue the aggregate particles together and impart strength when compacted and cooled down. As explained earlier, moisture damage is caused by the stripping of bitumen from aggregate particles. Therefore, the surface characteristics are the basic fundamentals of any mixture when designed for highway engineering or construction materials. It is recommended in future to explore in depth the surface energy related properties of a mixture and its correlation with the mechanical or strength characteristics of asphalt mixture to mitigate moisture damage problems.

Asphalt mixture moisture damage is identified while conducting tests on loose and compacted mixtures through qualitative and quantitative evaluations. Qualitative evaluation based on image analysis technique enables precise measurement of the extent of moisture damage if compared to visual inspection [59-61]. Conducting direct tensile test on compacted mixture is essential to measure the mechanical strength of asphalt mixture that can produce results based on quantitative measurements, followed by applying image analysis technique on the same sample fractured when subjected to direct tensile force. This will produce the qualitative analysis or measurement of stripping potential. Therefore, instead of conducting tests on loose and compacted mix separately to obtain qualitative and qualitative measurements, this method enables researchers to accommodate a single specimen for the evaluation of asphalt moisture damage. Moreover, this method can save time, material and minimize the possibility of errors which occur during sample preparation.

Research is being conducted at the Highway Engineering Laboratory, Universiti Sains Malaysia to identify the moisture damage in asphalt mixtures using image analysis technique. The technique quantifies the percent adhesion failure or stripping on surfaces that are fractured after failure in direct tension. This technique would be enhanced further to predict moisture susceptible materials used in highway construction [62].

## 8.0 CONCLUSION

This paper summarizes the findings obtained from the literature review on the basic aspects of moisture damage in asphalt mixtures and identifies gaps in knowledge for further advancement. There are various mechanisms that explain the process of moisture damage in asphalt pavements. Most likely, asphalt pavements experience moisture damage due to the interaction of several processes or mechanisms. It has been suggested that a single test method to evaluate moisture damage cannot be applied to a wide range of materials and conditions. Therefore, new laboratory based test procedure and analysis protocols should be developed which can simultaneously consider the effects of both traffic impact and moisture damage. Micro level studies based on asphalt aggregate interaction can contribute in terms of surface chemistry, which leads towards failures in asphalt mixture due to moisture. In addition, it is recommended that investigations should be conducted on pavement surface and subsurface drainage system to further mitigate moisture damage. Further investigations based on the construction techniques are required to simulate the design parameters used in the laboratory. In addition, improvement in the performance of WMA technology requires additional investigation on moisture damage. This is due to the presence of trapped moisture in the aggregates as a consequence of inadequate aggregate drying.

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