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Review Article

Analysis and Application of Pavement Interlayer Properties

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Abstract

The load varies with the thickness of the pavement, so there are different layers in pavement structures, between which interlayer interfaces contacting with each other inevitably in different modes. In this paper, based on investigation and analysis, the interlayer contact modes of pavement structures are classified as "interlayer coupling" and "interlayer connection", which are defined according to their mechanical properties. Based on the existing ordinary cement concrete pavement, this paper analyzes the formation, development and evolution of interlayer coupling, and finds that the failure of interlayer coupling is the cause of early pavement damage. Cement pavement structure with isolating course is proposed as a method and countermeasure to eliminate these hazards, the feasibility of which is verified theoretically. Conditions and approaches achieving interlayer connection in pavement structures are proposed as well. Application of interlayer connection is introduced using a novel type of polymer skeleton porous concrete pavement structure as an example.

Keywords: pavement design; interfaces; bond; roads & highways; structural analysis

List of notations

σ	is the stress of the interface.
$[\sigma]$	is the strength of the interface.
σ_1	is the stress of one layer of the two coupled layers.
$[\sigma]_1$	is the strength of one layer of the two coupled layers.
σ_2	is the stress of another layer of the two coupled layers.
$[\sigma]_2$	is the strength of another layer of the two coupled layers.

Introduction

Pavement for direct vehicle travelling can be a one-layered or multi-layered road structure (Al-Khateeb, 2020). It is built with a variety of road materials under different preparation methods and construction procedures on top of a subgrade. There are both similarities and differences between different pavements in terms of their mechanical properties.

Starting with mechanical properties, pavement is generally divided into two categories: rigid pavement, and flexible pavement (Hamdar and Chehab, 2017). The rigid pavement usually refers to cement concrete pavement, commonly known as the white pavement, like plain cement concrete pavement, reinforced concrete pavement, etc. It is of high strength, high rigidity, and good overall performance with fast stress dispersion ability. The theory of elastic foundation plate is used for the pavement structure design calculation. Flexible pavement mainly refers to all types of asphalt pavement, commonly known as the black pavement. It is of low rigidity. Under loading, it yields to large surface deflection and subgrade deformation (Qian et al., 2019). Thus, the overall strength of pavement structure is greatly dependent on that of the subgrade and base. The pavement is elastic, flexible, seamless and comfortable for riding on automobiles. The theory of elastic multi-layered system (Pereira and Pais, 2017) is used for the pavement structure design calculation.

Pavement is usually constructed layer by layer with different materials based design requirements and availability of local materials. Generally, low and medium-grade pavement structures are composed of fewer layers, including surface, base, bed courses and so forth, while high-grade pavement structure is composed of more layers, including surface, binder, base, subbase, bed courses and so forth (Badawy and Chen, 2020).

B Irrespective of rigid or flexible pavement, interface exists between different layers of pavement structures. However, so far, there are no studies on interlayer contact modes, their mechanical properties or the significance of their application in pavement structure. In this paper, the interlayer contact modes are classified and defined, and the mechanical properties, application and significance of contact modes between various interlayers have been analysed.

Combination and separation between Layers

In pavement structures, interlayer state is divided into two types, i.e., interlayer combination, and separation. In the combination state, two bonded layers constitute a composite plate to bear the stresses as one combined layer. On the other hand, in the separation state, individual layers respectively and independently bear the stresses which are transmitted between the layers through interlayer friction and contact.

According to the mechanism, the stress state of interlayer combination is far better than that of interlayer separation. First, the combination changes the stress state of the structure layers, which makes it possible for the surface layer in tension to change to a state of compression or partial compression. Second, the flexural-tensile state is an unfavourable condition in pavement structure. Based on the material mechanism, the maximum flexural-tensile stresses decrease significantly with increasing components' thickness. Therefore, the interlayer combination is very effective in stress reduction.

Despite of its advantage in stress reduction, it is difficult to ensure the layers stay in the combination state. Further, as the interface is a weak layer in the pavement structure, it needs to bear the shear and tensile stresses caused by the traffic and other external loads. Thus, a special design is needed to achieve the interlayer combination. The followings are some of the measures taken to ensure interlayer combination. Using of the shear key to combine the pavement layer and the concrete bridge deck. The roughing treatment to the concrete interfaces between different concrete pours at different times. Despite of these measures, a perfect interlayer combination cannot be guaranteed.

On the other hand, the interlayer combination can be achieved and maintained with improvement in materials and other techniques. For example, there is an emerging chemical technology such that the bonding performance of adhesive materials can be equal or exceed that of structure materials. Hence, once the layer materials can meet the stress-bearing requirements, it is feasible to create interlayer combination through interface material selection, interface mode treatment and so forth. In accordance to specified structure design, different layers can bear the stress as one integrated layer.

Two typical interlayer contact modes

According to the conditions and mechanical characteristics of interlayer connection and based on the results of a field investigation, interlayer contact modes of pavement structures are divided into two categories, i.e., "interlayer coupling" and "interlayer connection".

Interlayer coupling

Definition and identification

The term "interlayer coupling" describes the connection between various layers of pavement structures where the layers are bonded in the initial state. However, when the layers are subject to external loading, they become separated at the interface or near its geometric location due to the soft binding materials. The two debonded layers therefore cannot bear the stresses as one integrated layer.

The essence of interlayer coupling is that the layers are initially bonded but subsequently become separated. If the adhesive bonding of structure layer material in the vicinity of interface is weak, separation failure occurs in the material. Hence, the initial bonding state cannot be maintained, and the layers are eventually separated.

By definition, the "interlayer coupling" can be identified according to the following relationship:

$$\sigma \geq [\sigma], \text{ or } \sigma_1 \geq [\sigma]_1, \text{ or } \sigma_2 \geq [\sigma]_2 \quad (1)$$

Where, $[\sigma]$ is the interface strength; $[\sigma]_1$ and $[\sigma]_2$ are the strengths of two coupled layers, respectively; σ is interface stress under loading and environment impact; σ_1 and σ_2 are the stresses of the two coupled layers.

Further, the "Interlayer coupling" can be divided into two types, i.e., "strong coupling" and "weak coupling".

Strong coupling

Strong coupling is the coupling in which the interface bonding strength is greater than the shear strength (i.e. no interface shear failure or tensile strength (i.e. no interface tensile failure) of either of the two connected layers.

The conditions for strong coupling can be expressed as following:

$$\text{or } \sigma_1 \geq [\sigma]_1, \text{ or } \sigma_2 \geq [\sigma]_2 \quad (2)$$

Where $[\sigma]$ is the interface strength, $[\sigma]_1$ and $[\sigma]_2$ are the respective material strengths of the two connected layers. After the destruction of the strong coupling of the coupled layers (or one of the coupled layers) near the coupling interface, its characteristic is not retained as the interface itself is damaged. After the failure of the strong coupling, the separation damage does not occur along the geometric contact interface of surface and base course. It occurs near the geometric interface, inside the layer with weak adhesion strength, and part of the destroyed layer is attached to the non-damaged layer.

Given that the strong coupling is destroyed as the layer with weak strength is destroyed (the separation damage is in the inside and it is fractured), the damaged surface is characterized by tortuousness, stagger, roughness and local fragmentation. In this case, due to various external actions, the two separated parts cannot be bonded along the damaged interface anymore and are often in non-uniform contact or void state.

Weak Coupling

Weak coupling is the coupling in which the interface bonding strength is less than the individual shear strength or tensile strength of either of the coupled layers. The weak coupling generally fails as the interface is damaged. The coupling conditions are:

$$[\sigma] \leq [\sigma]_1, \text{ and } [\sigma] \leq [\sigma]_2 \quad (3)$$

After the separation, only the interface connection is damaged, and there are no obvious adherents on either of the two coupled layers. The impact of the separation is limited to the interface only. The separation and relative movement of the two layers, even if it is very tiny, still produces some inhomogeneous void in the contact interface.

As indicated by the above analysis, irrespective of strong or weak coupling, separation damage eventually occurs, resulting in a non-uniform interlayer support state. However, the locations of failure are different, which leads to different levels of interface deterioration. Generally, the level of interface damage in weak coupling is less as compared that in strong coupling.

Interlayer connection
Definition and identification

The term “interlayer connection” describes the connection where two structure layers that are fully bonded. Both the interface and the layer materials can resist external loading and environmental impact, and the two layers act as one system to bear the stresses.

For layer combination, two conditions must be met and they are essential to interlayer connection. First, the interface must remain intact, which means interface adhesion should be able to resist external loading and environment impact like interface shear stress, tensile stress, etc. Second, the structure layers on both sides of the interface must also remain intact, which means that the layer materials should meet the strength and deformation requirements under external loading and environment impact.

By definition, the interlayer connection can be identified according to the following relationships:

$$\sigma \le [\sigma], \text{ and } \sigma_1 \le [\sigma]_1, \text{ and } \sigma_2 \le [\sigma]_2 \qquad (4)$$

Where [σ] is the interface strength; $[\sigma]_1$ and $[\sigma]_2$ are the strengths of two connected layers, respectively; σ is the interface stress under external loading and environment impact; σ_1 and σ_2 are the stresses of the connected layers, respectively.

Mechanical characteristics of pavement in interlayer connection

By the definition of interlayer connection, due to interlayer connection, structural layers are completely bonded to form one composite layer. If an interlayer connection is located between the surface and the base course, in mechanics, the new layer formed can be regarded as a composite plate. Under traffic loading, flexural and tension strength occur above and below the neutral axis of the plate, respectively. The composite plate has two functions. First, under the external loading, it places the surface layer in a favourable stress state with whole or partial compression, thus effectively use the high compressive strength of pavement materials (Wang et al., 2017). Second, it reduces the flexural-tensile stresses at the bottom of the plate to improve the stress distribution of the base course. Hence, the stress distribution of the pavement structure is completely changed by the interlayer connection, which is especially suitable for pavement structures with a thin surface course or wearing course.

For pavement structures with a thin surface or wearing course, in some cases, the surface layer produces great flexural-tensile stress under vehicle loading. This is unfavourable for the surface layer and impacts its durability, if the surface materials are paved on smooth and uniform base without being bonded to it, even though they have excellent mechanical characteristics of strength and deformation. Moreover, if the surface course is not adhered to the subsurface course, it is a thin plate structure which may produce buckling stability problems with compression increase because of temperature increment (continuity of pavement leaves surface layer with insufficient free expansion). Therefore, it is the key for the combination design of thin layer pavement structures to adhere the surface to the base so that they bear the stresses as a whole.

Realization of interlayer connection

The interlayer connection is absolutely achievable by using adhesion agents, interface processing methods and other techniques, although it is difficult to do so.

To achieve interlayer connection, first, strong adhesion is required. Second, the materials near the interface should meet the corresponding binding strength and deformation requirements to prevent separation failure within the interface or base course. Hence, the surface conditions and base materials play an important role in ensuring that the adhesive layer works well. Otherwise, bonding failure may occur and the expected performance cannot be achieved. To ensure realization of the interface connection in pavement, efforts may be made in the following aspects.

First, appropriate interface binders can improve the bonding performance between the surface and the base course (Yuan et al., 2018). As the efficiencies vary with different binders, the binding materials should be designed according to the specific application.

Second, the base surface should be roughened or indented in order to improve the mechanical interlocking force and biting force.

Third, base materials of sufficient strength should be used to avoid the invalidation of adhesion bond resulting from base material failure.

Hazards and countermeasures for cement concrete pavement with interlayer coupling

Formation and destruction of interlayer coupling

As far as ordinary cement concrete pavement is concerned, the interface connection between the surface and the base course is a typical interlayer coupling. Its formation, development, evolution and the hazard are analysed as follows.

The procedure for constructing a cement concrete pavement generally consists of concrete mixing, transporting, paving, vibration, surface treatment, kerf and health. Before the pavement is laid, the base should be cleaned, followed by pouring plastic-state concrete directly on top of it (Alexander et al., 2017). The pavement can be open to traffic after the concrete is set and reaches certain strength. As can be seen from the construction process of cement concrete pavement, the grout penetrates into the base course and the surface and base course are bonded together at the beginning of casting, which obviously is very favourable for the surface to bear the stresses if the cement concrete pavement can maintain its initial state. However, the initial conditions do not last long (Li and Xu, 2018). Both theoretical and experimental results showed that the separation damage of surface and base course is inevitable. During the process of hydration and solidification of cement concrete, the elastic modulus, Poisson's ratio and strength of surface layer materials constantly vary. The separation damage inevitably occurs because of the mismatch of material characteristics in the surface and base layers and the shrinkage during the surface concrete condensation, which makes it difficult to maintain the ideal smooth contact state between the surface and the base layer.

Hazard of interlayer coupling

In the traditional pavement design calculation, it is assumed that the surface layer is separated from the base layer. However, in practice, the surface layer and the base layers are bonded first and then separated. After the interlayer coupling is destroyed, the composite plate formed by the surface and the base course no longer exists. The stresses at the bottom of the surface layer under the non-uniform support conditions change from compression or tiny tension to tension state. Extensive stress concentration appears at the surface course under the vehicle and temperature buckling loading, and the bottom of the surface course is also placed in an extremely unfavourable tension state.

The damage caused by the interlayer coupling separation is also the evolution process of supporting boundary conditions between pavement layers. The essence of interlayer separation is interlayer failure. Separation damage leads to the non-uniform support of cement concrete slabs, the cracking and breaking of the base course. This loss of integrity of the base course results in significant discrepancies between the real pavement interlayer conditions assumed in the design calculation. This is the root cause why the actual service life of ordinary cement concrete pavement is much shorter than its design life.

Therefore, the bonding between the surface and base course of cement concrete pavement is a typical interlayer coupling. Separation damage inevitably occurs so that the surface layer is placed under an extremely unfavourable non-uniform support state, which causes significant discrepancies of the real pavement situation with the premise of the mechanics model, deviates from the assumptions of theoretical model and results in severe early diseases of concrete pavement. In other words, interlayer coupling is the root of the problems of cement concrete pavement

Countermeasures for interlayer coupling hazard- setting isolation layer for cement concrete pavement structure

Since it is understood that the failure of interlayer coupling is the cause of early pavement damage, it is not difficult to solve the problem.

Theoretically, separation damage can be avoided by eliminating the interlayer coupling between layers. Thus, to realize the transition from "passive" separation to "positive" separation and match real interlayer conditions with the premise of the theoretical model, so that the actual concrete service life reaches or approaches its design life.

Theoretically, by eliminating the interlayer coupling between layers to avoid separation damage, the transition from "passive" separation to "positive" separation can be realized. By further matching the real interlayer conditions with the premise of the theoretical model, the actual service life of concrete can be made to reach or approach its design life.

Some earlier research showed that setting thin film isolation layer between the base and surface course could prevent cement concrete slurry from penetrating into the base and forming the transition layer during surface grouting. In this way, the formation of interlayer coupling is eliminated, thereby preventing passive separation damage and eliminates three basic interlayer damages caused by the interaction of surface and base course. Hence, the pavement structure with smooth contact between the layers is consistent with the assumptions in the theoretical model. The actual pavement interlayer state also meets the "three premises" of the theoretical model. As such, the bearing capacity and service life of the pavement with a thin film isolation layer can reach the design expectations. On the other hand, the traditional concrete pavement structures have failed to reach the expected design life.

Interlayer connection in novel polymer skeleton porous concrete pavement (PSPCP)

The typical application of interlayer connection is introduced below using a novel PSPCP with the interface bonding layer.

Material constitution idea based on skeleton porous structures and the structure of the novel pavement

In order to overcome the deficiencies of conventional packing concrete, shrinkage for example, by using polymer modified cement binder as nodes, a statically indeterminate spatial grid structure is put forward with the form of "skeleton + nodes+ pores" (figure 2), which was based on the theories of granular material mechanics and conventional structural mechanics, thus forming a new kind of composite material named Polymer Skeleton Porous Concrete (PSPC).

Figure 1: Coring of cement concrete pavement with interlayer coupling between surface layer and base course.

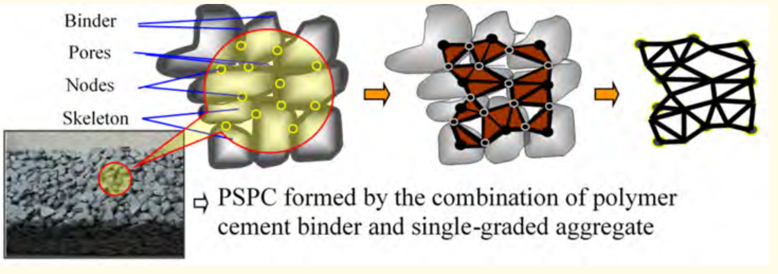

Figure 2: Organigram of PSPC.

The skeleton porous structures, whose material constitutional mechanisms are clearly different from those of ordinary packing cement concrete, can help decrease relatively high secondary stresses caused by temperature deformation or shrinkage deformation, achieve continuous paving without slab cutting and avoid the cracking and breaking of the pavement due to secondary stresses. Thus, such structures build up the foundation for the achievement of interlayer connection between the surface course and the base course. The typical form of a polymer skeleton porous concrete pavement structure is as follows:

A structural surface course + an interface bonding waterproof layer + a high strength base course+ a low strength base course, which is shown in figure 3.

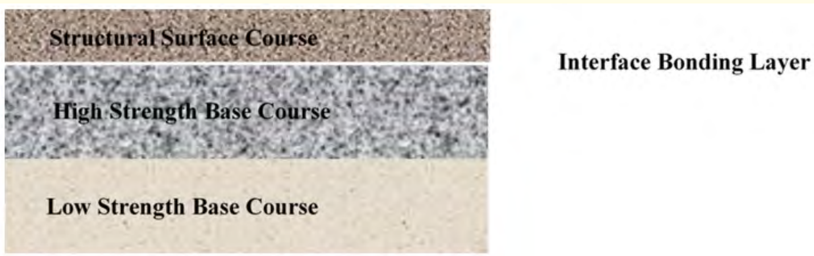

Figure 3: Typical structure of PSPCP (cross section).

Among all the layers, the thicknesses of the functional surface layer and the interface bonding waterproof layer are negligible. The interface bonding waterproof layer is formed by solidification of the mixture of polymer and cement. The structural surface course is formed by paving a layer of polymer skeleton porous concrete before solidification of the mentioned layer. The high strength base course can be in some forms, for example, in the forms of roller compacted concrete, ordinary cement concrete, or bridge deck and so on. The low strength base course is usually the same as the subbase for conventional cement or asphalt pavements.

Polymer binders with a good adhesion performance are adopted as the interface bonding waterproof layer and the neighbouring base course has a high strength. The interfacial connection form between the structural surface course and the high strength base course is a typical interlayer connection.

Assurance of interlayer connection in PSPCP

The realization of interlayer connection in the PSPCP has two requirements: on the one hand, the interlayer binding material should meet the bonding requirements; on the other hand, the material properties of the surface course and the base course should satisfy the requirements of stress bearing.

First, the interlayer bonding material should meet the bonding requirements.

Polymer binder is necessary to ensure interfacial adhesion. The modified polymer binder has a good bonding ability and can infiltrate into the voids of the old concrete. After the new concrete is hardened and the polymer film is formed, coupling bridge forms between the new and the old concrete, which greatly enhances interfacial bonding. The water retention properties of the polymer in the interface binder enable the cement to be adequately hydrated, which generates more hydration products to fill the voids in the concrete and strengthens the mechanical interlocking effect of bonding layer. Moreover, by adding polymer to the interface binder, its infiltration ability is enhanced and internal structure becomes compact, resulting in a thick, compact and strong bonded transition layer. Therefore, the polymer binder improves the interface bonding performance by improving the mechanical biting force and chemical force.

The interface bonding test shows that, under the same interface processing conditions, the bonding strength of interfacial agents generally increased by more than twice when a polymer cement interface binder is used as compared to the use of ordinary cement slurry. The adhesion between the surface and base course using polymer interfacial binder is shown in Fig. 3. In the layer adhesion test, first, the polymer skeleton porous concrete layer was bonded to the base course using polymer interfacial binder, followed by hammering horizontally the polymer skeleton porous concrete layer (as shown in Fig.4). Test indicated that the failure occurred in the interior of either the polymer skeleton porous concrete layer or the base course, which proved that the interface bonding strength is greater than material strengths of the polymer skeleton porous concrete layer and base course.

Figure 4: Adhesion of bonding material treatment of polymer-painted cement interface. (Cement concrete base course damage in the left, and surface course damage in the right)

Second, the material properties of the surface layer and the base course should satisfy the requirements of stress bearing.

The adoption of skeleton porous structure as the surface layer material, which has been stated in section 4.1, can overcome the interlayer separation due to external forces caused by such factors as shrinkage, temperature variation and so on, making possible the realization of interlayer connection. Meanwhile, as a polymer modified cement was used as the binder, PSPC can deform to a much greater extent and its ultimate deformation can reach 1000～2000 με, which is about 10-20 times of the ultimate flexural tensile deformation of ordinary cement concrete. It can greatly help achieve the deformation compatibility between the PSPC layer and the base course with interlayer connection.

Moreover, the design of base course materials is also necessary to ensure interlayer connection. Usually, the surface course often has a superior performance. Thus, the design of base course materials is the key to achieving interlayer connection. In the new pavement, a new roller compacted concrete base course with sufficient strength, ordinary cement concrete, bridge deck and so forth can be used for the purpose of base course construction. However, the cement stabilized layer, the lime-fly-ash stabilized layer and so forth used for conventional pavement are not suitable for this new type of pavement base course.

In conclusion, interlayer connection between the structural surface course and base course can be achieved, with the specific polymer interface binder chosen and the special design of base course materials.

Application effect of PSPCP

PSPCP is well known for its good permeability, noise reduction, color and other service functions, but the improvement of pavement service functions needs to be accomplished relying on the structural durability of pavement which is realized through interlayer connection between layers.

The advantages of PSPCP are its great compressive strength and deformation performance, and the composite plate formed between surface and base course by interlayer connection embodies the pavement design idea of “double insurance”: on the one hand, the overall surface concrete is under a long-term favourable high compressive stress state, which gives full play to the high compressive bearing capacity of the pavement materials. On the other hand, a sufficient deformation space for surface concrete is reserved to avoid the flexural-tensile damage due to local abnormal void and abnormal flexural deflection and the pavement diseases due to surface material degradation.

At present, PSPCP has been successfully and widely applied in road construction.

Conclusions

In this paper, by analysing the interlayer contact modes of pavement structures, the main results and conclusions are:

1. The interface contact modes between layers of pavement structures are classified as “interlayer connection” and “interlayer coupling”, which are then defined respectively.
2. The formation and mechanical characteristics of interlayer connection and interlayer coupling are analysed and discussed.
3. The formation and hazards of interlayer coupling are analysed with current ordinary cement concrete pavement used as an example. The interlayer design principle of cement concrete pavement with an isolation layer is analysed.
4. The application and performance of interlayer connection are analysed using a new type References of PSPCP with an interface bonding waterproof layer.

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Disclosure Statement

The authors declare that they do not have any competing financial, professional, or personal interests from other parties.

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