Challenges of Electrical Road System (ERS) towards DPWT

- Load durability of non-contact wireless power transfer pavement -

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ABSTRACT: It is hoped that the introduction of electric vehicles will be promoted as a form of mobility that will help reduce CO_2 emissions, a cause of global warming. To promote the introduction of EV vehicles, research is underway on Electrical Road System (ERS) in which DWPT coils that can supply power while driving are embedded in the pavement.

This paper summarizes the results of embedding magnetic resonance-type non-contact power transmission coils in the pavement, FEM model analysis, and running load tests using large vehicles.

KEY WORDS: Dynamic wireless power transfer, Pavement, ERS, FEM, Resin mixture

1. INTRODUCTION

The introduction of electric vehicles is being promoted in the transportation sector as a measure to combat global warming. There is a need to establish contactless power supply technology to reduce the weight of electric vehicle batteries.

The objective of this study is to improve the electrical and mechanical properties of the coils (including the coil case) used for wireless power transmission while driving when embedded in the pavement, and to establish a coil design and embedding technology that can ensure long-term durability when embedded in asphalt pavement on which moving large tracks[(1),(2)].

We evaluated the mechanical properties of the power supply coil embedded in the pavement (strength against embedding work and loads from automobiles) and the mechanical properties of the asphalt pavement with the coil embedded (strength and durability of the pavement).

2. DWPT SYSTEM

2.1. Installation of coils on the pavement of the Public Works Research Institute's test track

The purpose of the repeated running tests on the circular track in the Public Works Research Institute's pavement running test facility (hereafter referred to as the circular running track) was to verify the strength and durability of the power supply coil and the pavement, and to verify changes in electrical and mechanical properties before and after the running tests. A repeated load test was carried out in which a loaded vehicle ran on the circular running track. Figure 1 shows the test location in the pavement running test facility.

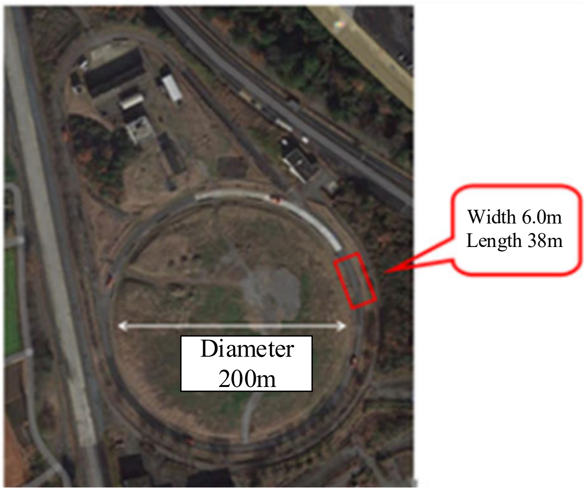


Fig.1 Public Works Research Institute's circular track and test construction site

The coils were embedded in a pavement structure designed to support 1 million passes of a design traffic load of 49 kN. Immediately after embedding the coils, electrical properties, FWD deflection, and road surface shape surveys were conducted, and electrical properties and FWD deflection surveys were also conducted after the running test, and durability was examined from the results before and after running a large vehicle.

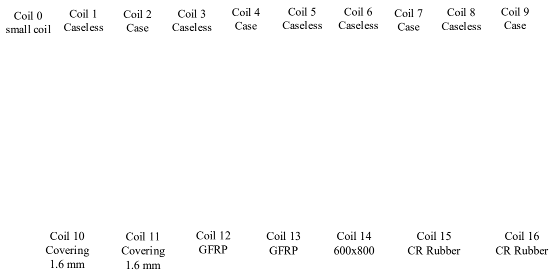


Fig.2 Pavement structure with buried coils

Fig.3 Position plan view (planar position of coil).

Table1 Type and buried position of coils installed on the circular running road

Coil	Case material	Coil Type	Litz wire conditions	Depth	Posicion
1	Caseless	Short	φ8 mm, 0.05mm, 10,000 pieces, FEP coating	Binder	BWP
2	Polycarbonate	Short	φ8 mm, 0.05mm, 10,000 pieces, FEP coating	Binder	BWP
3	Caseless	Short	φ8 mm, 0.05mm, 10,000 pieces, FEP coating	Surface	BWP
4	Polycarbonate	Short	φ8 mm, 0.05mm, 10,000 pieces, FEP coating	Surface	BWP
5	Caseless	Short	φ8 mm, 0.05mm, 10,000 pieces, FEP coating	Binder	IWP
6	Caseless	Short	φ8 mm, 0.05mm, 10,000 pieces, FEP coating	Binder	IWP
7	Polycarbonate	Short	φ8 mm, 0.05mm, 10,000 pieces, FEP coating	Binder	IWP
8	Caseless	Short	φ8 mm, 0.05mm, 10,000 pieces, Thread coating	Surface	IWP
9	Polycarbonate	Short	φ8 mm, 0.05mm, 10,000pieces, FEP coating	Surface	IWP

The existing pavement structure at the experimental site was a surface course of 50 mm, a binder course of 50 mm, base course of 250 mm, and a subbase course of 300 mm, with the standard bearing capacity of the subgrade being CBR=6. When burying the coils, the existing surface and binder courses were removed, and the coils were buried at the same time as the binder and surface courses were laid. As shown in Fig. 2 and Fig.3, coils 1 to 4 were buried in the BWP (Between Wheel Path) between the wheels of a large vehicle, and the coil and pavement durability was evaluated when the wheels did not pass directly above the coils. Coils 5 to 9 were buried in the IWP (Inner Wheel Path) where the wheels pass, and the coil and pavement durability was evaluated when the wheels pass directly above the coils. Table 1 shows a list of the coil embedding experiment conditions at the Public Works Research Institute's circular pavement running test site. By using litz wire with a wire diameter of 0.05 mm and 10,000 wires, the design can achieve a high power of 50 kW, making it suitable for large vehicles. The coating is made of Fluorine resin (FEP) material with a thickness of 0.5 mm.

Fig.4 FWD measurement on pavement with embedded coils

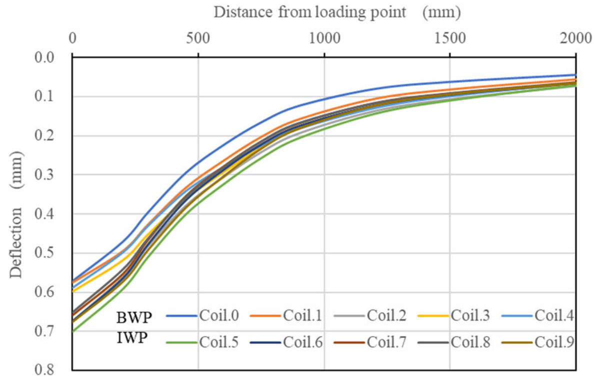


Fig.5 Deflection curve of coil buried location

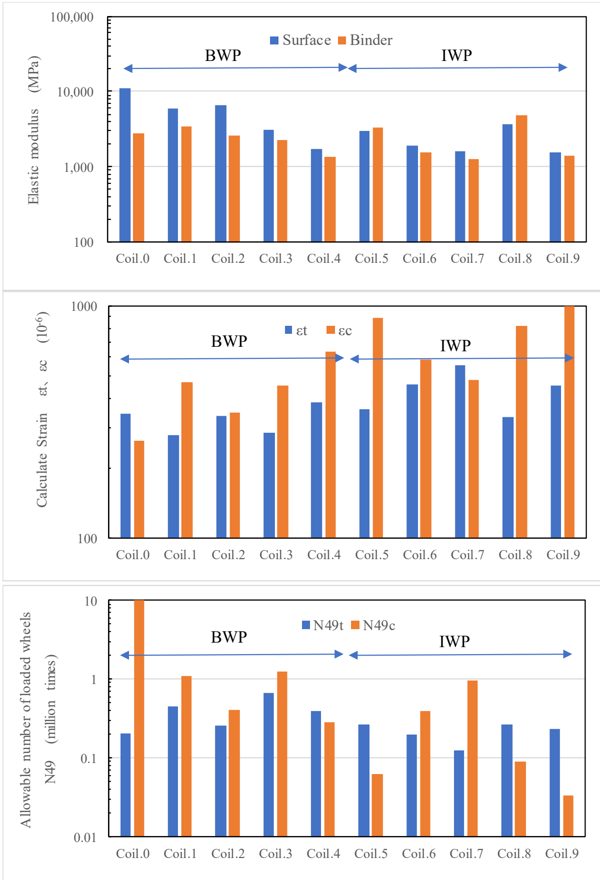


Fig.6 Comparison of the layer elastic modulus of each layer, calculated strain, and allowable number of load cycles

2.2. Mechanical properties of non-contact power supply pavement.

The pavement structure was evaluated using an FWD device that measures the deflection of the pavement by impact load from a falling weight. For the measurement, a loading plate with a diameter of 300 mm was placed at the loading point, and a 120 kg weight was allowed to free fall from a height of 150 mm, applying an impact load of 49 kN to the pavement surface. The FWD measurement situation on the pavement with the coil embedded is shown in Fig.4. The deflection curve measured at the point where the coil was embedded is shown in Fig.5.

Comparing the deflection when the coil was embedded in the binder layer and when it was embedded in the surface layer, there was a difference in the shape of the curve at a point 300 mm away from the loading point.

Here, the elastic modulus of each layer was analyzed by back-calculation analysis (BALM)[3] based on a multi-layer elastic calculation program, so that the deflection would match the pavement structure. Using the elastic modulus obtained, the horizontal tensile strain on the bottom surface of the asphalt mixture and the vertical compressive strain on the subgrade surface were calculated using multi-layer elastic analysis. From these results, the allowable number of load wheels was calculated using the fatigue failure criterion formula[4] proposed by the American Asphalt Institute. These results are shown in Fig.6.

When comparing the elastic modulus of layers including embedded coils, although there were differences in conditions such as the embedding location, the elastic modulus of the asphalt mixture with embedded caseless coils was found to be the highest.

The tensile strain of the underside of the asphalt mixture base layer was smaller for the caseless coil, which is made of Litz wire coils reinforced with a resin mixture, than for the base layer with a coil case. The durability of the caseless coil pavement structure is predicted to be high.

For the BWP, the elastic modulus and allowable number of wheels do not decrease regardless of the coil burial method. On the other hand, under conditions where the case coil is buried in the surface layer where the wheels pass, cracks occur around the coil due to the running of a large vehicle, and the elastic modulus of the base layer tends to decrease. There is a clear difference in the strength of the coil installation between the BWP at the center of the lane and the IWP at the wheel passing position, and the number of wheel passes has a large effect.

3. FEM analysis

3.1. Introduction

In non-contact power supply pavement, a coil case made of resin is embedded in the pavement to protect the coil made of Litz wire. A resin adhesive is used to integrate this case with the pavement, but the adhesive effect is not clear in the elastic analysis model. Therefore, we decided to use a finite element analysis model (hereinafter FEM analysis) to examine the effect of the coil case existing in the pavement. The calculation program used was PAVE3D, which was developed by Nishizawa for pavement analysis.

3.2. Analysis model

This analysis model is composed of 8-node hexahedral elements (solid elements) as shown in Fig.7, and the amount of deformation within the element can be calculated from the displacement of each node. The displacement within the model is calculated by solving the following matrix, where Ni is called the shape function. As is clear from the form of this shape function, the displacement is a linear function within the element. Therefore, care must be taken when dividing the elements when the displacement changes in a higher order.

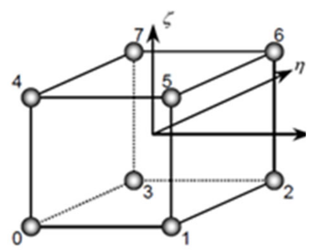


Fig.7 Contact solid element

3.3. Element division

When creating the mesh, the area around the loading point was treated as a collection of fine elements, while the elements away from the loading surface were treated as coarse elements. Model analysis was performed on two types of pavement configurations at the Public Works Research Institute's pavement running test site: a structure with a coil case in the base layer and a structure with a coil case installed on the surface layer.

The analysis model was created as a 1/4 model, taking symmetry into consideration, to reduce the number of elements. The element model was set to an area of 3 m in length and width and 3 m deep from the center. An example of the overall mesh division is shown in Figure 8. The element division was set to 50 mm near the loading point, and 100 mm, 150 mm, and 300 mm according to the distance. The calculations were compared under two conditions: rough and smooth bonding surfaces between the case and the pavement.

The layer for embedding the coils was divided into elements for the asphalt mixture and the open-type and DD-type coil cases (polycarbonate resin) and mesh modeled. The element division model for the coil installation layer is shown in Fig.9. In this figure, the model is loaded on the edge of each coil case.

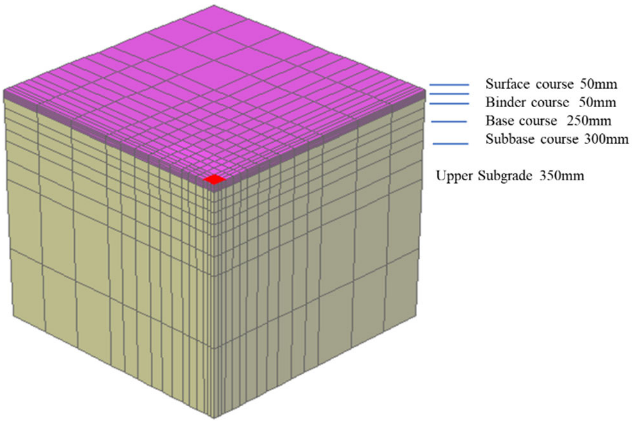
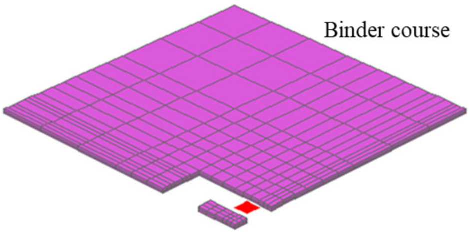
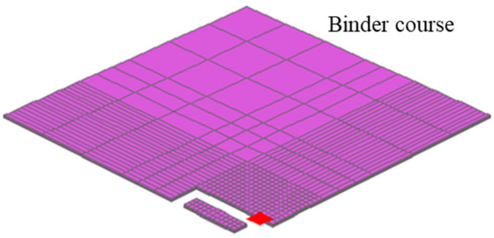


Fig.8 Mesh diagram for pavement structure analysis (1/4 model)



(a) Side Load on the O type Coil case

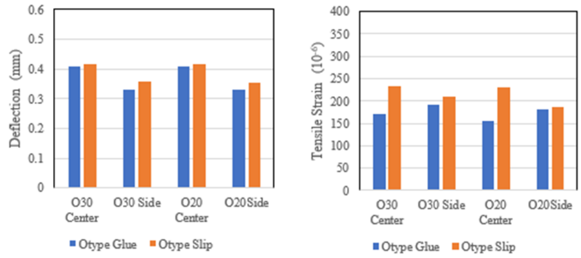


(b) Side Load on the DD type Coil case

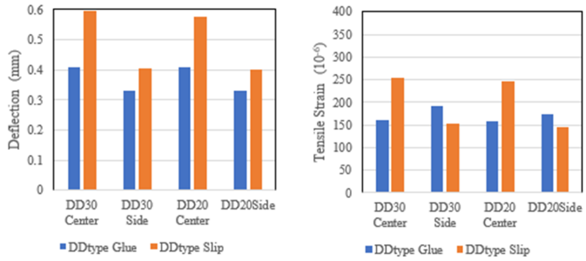
Fig.9 Shape and loading position of coil case buried in base layer

3.4. Analysis results for binder layer buried coil

Since the coil case was made from a polycarbonate plate, the bending rigidity of the material in the test results sheet was used as a reference and the elastic modulus was calculated as 2000 MPa. The elastic modulus of the MMA adhesive was 4000 MPa. The elastic modulus of each pavement layer was analyzed as 8000 MPa for the surface layer, 6000 MPa for the binder layer, 200 MPa for the base course, 70 MPa for the subbase course, and 80 MPa for the subgrade, based on the back calculate of the elastic modulus from the FWD loading test of the OWP without the coil buried in it.



(a) Deflection and tensile strain of the open-type coil



(b) Deflection and tensile strain of the DD-type coil

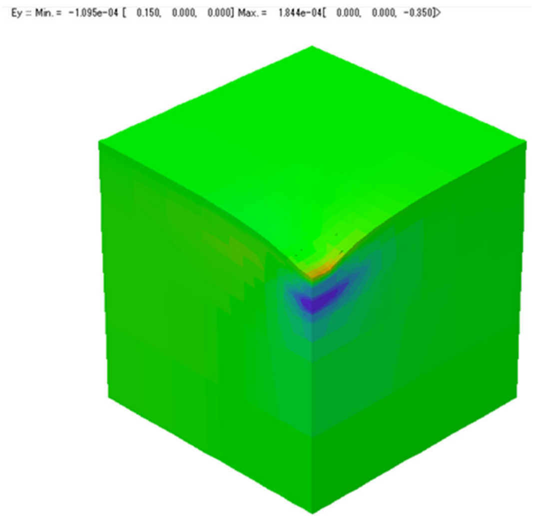
Fig.10 Comparison of deflection and tensile strain obtained by FEM analysis

Comparing the deformation at the center and the deflection at the side, when the case thickness is 30 mm, the difference in horizontal tensile strain is greater than the difference in deflection between rough and slipping. When the coil case thickness is 20 mm, the thickness of the different materials is thinner, so the difference in deflection is smaller and the difference in strain is also smaller.

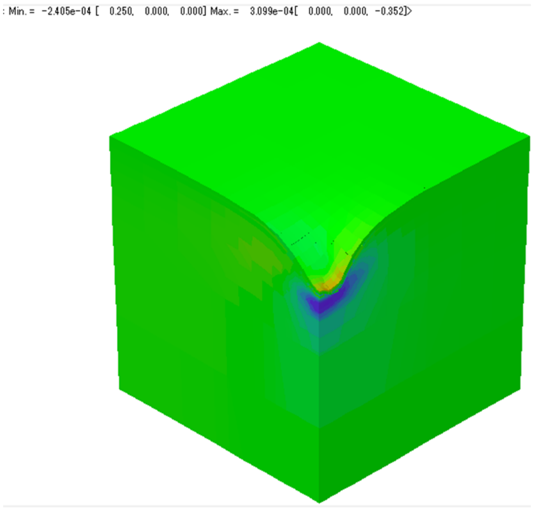
As a result, the thinner the coil installed in the pavement, the less the influence of the polycarbonate case is, and the easier it is to integrate with the pavement.

This is because we are looking at the influence of the adhesive surface (slip), so the difference between when the load is at the center and when it is at the side is greatly apparent. DD coils have a beam in the center, making them resistant to twisting, so even with slippage from side loading, the deflection and horizontal tensile strain tend to be smaller than those of the open type.

A comparison of the horizontal tensile strain contours (3D display) for the rough and slip base embedment in binder layer is shown in Fig.11. There are differences in the deformation of the side load on the pavement and coil case and the distribution of tensile strain, but the contour diagram shows that in the slip base with no adhesive strength on the bottom of the coil case of the binder layer, large tensile strain occurs not only on the bottom of the binder layer but also in the upper base course. This makes it clear that the influence of adhesives is important to make the behavior of solids of different materials embedded inside the pavement similar to that of the pavement.



(a) O type Coil Side loading, Tensile strain, Rough



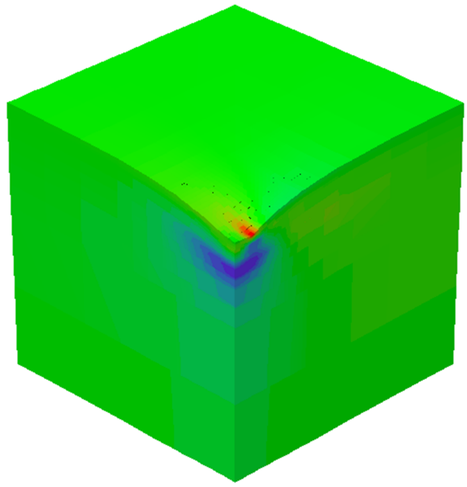
(b) O type Coil Side loading, Tensile strain, Slip

Fig.11 Comparison of contour plots of horizontal tensile strain due to coil case in binder layer

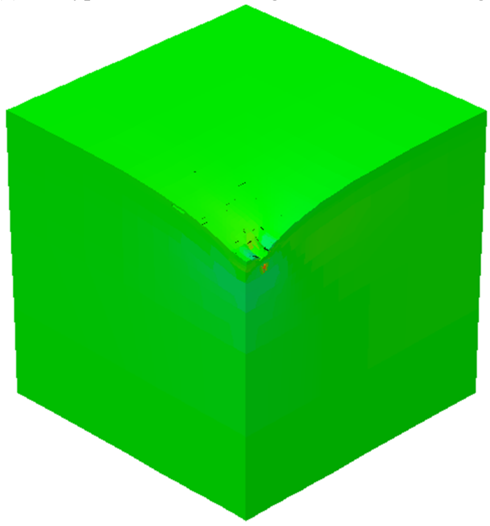
3.5. Analysis results for Surface layer buried coil

Figure 12 shows a comparison of horizontal strain contours (3D display) when the coil case is installed on the surface layer. When the coil case is installed on the surface layer, the difference in shape and size of the deformation (deflection) of the load on the pavement surface is larger when the load is applied to the pavement surface and directly on the coil case than when the load is applied on the coil.

When there is no adhesive force on the underside of the coil case on the surface layer (sliding between layers), the compressive strain on the surface is smaller than that of the base layer. However, horizontal strain occurs on the underside of the base layer and the upper roadbed, and especially under sliding conditions, large horizontal strain occurs at this position, and differences in the contour shape also occur.



(a) O type Coil Side loading, Tensile strain, Rough



(b) O type Coil Side loading, Tensile strain, Slip

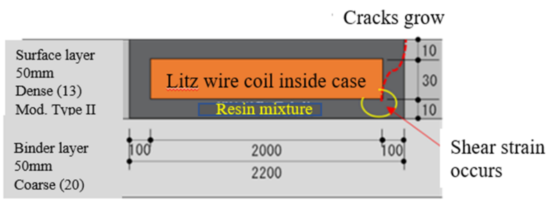
Fig.12 Comparison of contour plots of horizontal tensile strain due to coil case in surface layer

Table 2 Caseless Litz wire coil fixed to the surface with resin

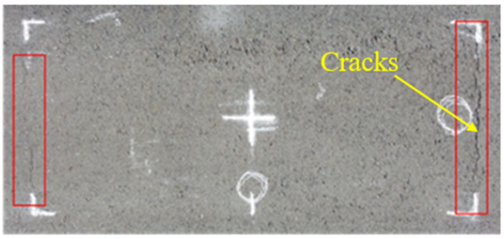
Irem		Litz wire coil + resin	
		Central	End
Deflection D0	(mm)	0.408	0.331
As Mix tensile strain	(10^{-6})	155	102
Base course tensile strain	(10^{-6})	215	180
Subgrade compressive strain	(10^{-6})	436	357
Shear strain	(10^{-6})	265	193

This shows that when objects of different materials are buried in the pavement on the surface layer, there is a high possibility of warping and peeling due to sliding, so in order to make them behave in the same way as the pavement, the influence of the adhesive is greater than that of the base layer. For this reason, it is important to select the type of adhesive and adhesive strength to bond the asphalt and the coil case.

Table 2 shows a comparison of deflection and strain at different loading positions when a caseless litz wire coil is used



(a) Model showing cracks progressing from the boundary between the resin mixture and Asphalt mixture



・Cracks have developed at the boundary between the resin mixture and the Asphalt mixture. Fine grains have partially erupted.
⇒ **Installation of shrinkage joints and joint injection material are required.**
・No progress in damage due to increased use of large vehicles.

(b) Road surface condition where cracks appeared after 200,000 vehicles

Fig.13 Damage to the coil with case at the IWP

on the surface layer and fixed with resin (h=2cm). Compared to central loading where there is no litz wire, the edges have less of an effect from the resin and less deflection. Regarding strain, the strain generated on the underside of the asphalt mixture and on the top surface of the roadbed is smaller than under other conditions, and the integration of the pavement and coil structure has a greater effect. For surface layer installation, since it is close to the vehicle running surface, it requires even greater integration than if it were buried in the base layer. In that respect, the method of integrating a caseless litz wire coil with resin appears to have advantages over cased coils.

4. Conclusion

When installing a coil case for DWPT on a pavement, a boundary occurs between the pavement material and the resin of the coil case in terms of deformation and stress/strain of the pavement. However, because the pavement and the buried coil were bonded together, the study was conducted as a continuous elastic body, and the damage mode was different.

A study was conducted on pavement with buried DWPT using a finite element analysis model corresponding to the actual situation. The results are summarized below.

1. When comparing loading at the center of the coil case with loading at the edge of the coil case, the surface deformation (deflection amount), horizontal strain on the bottom surface of the coil case, and compressive strain on the top surface of the roadbed when loading the pavement at the edge of the coil are larger than those at the center of the coil. This is because shear stress and shear strain occur at the boundary between different materials on the bottom surface of the loading edge, and it became clear that the continuity of the bottom surface and side surface (vertical direction) has a large effect on strain when studying fatigue resistance, resulting in lower fatigue resistance.

2. In a sliding state with weak adhesive strength, these effects are further increased, with deformation increasing by about 1.4 times and strain increasing by about 1.5 times between surface installation and base installation.

3. The difference in deformation between surface installation and base installation of the coil case is about 1.4 times, and strain is about 1.2 times, and this tendency occurs regardless of the influence of adhesive strength. For this reason, there is also an influence of restraint due to the dead load of the mixture placed on the coil case. As shown in Figure 13, it is presumed that cracks will progress toward the top surface of the pavement due to the influence of shear strain on the side of the coil case. When installing the power supply coil, it is necessary to consider the installation of a contraction joint between the coil case and the pavement.

4. Since the DD type coil case has a beam in the center, it has high rigidity due to being buried, and when it is integrated with the pavement, deflection and strain are small. However, when the adhesive surface is sliding, the influence of the stiffness of the coil case is likely to appear in areas away from the loading position when installed on the surface. When installing on pavement, it is important to consider the installation location and condition, as it will be affected by whether or not there is restraint due to loading on top, the adhesion state (integrity) of the coil case to the pavement, and the position where the wheels of traveling vehicles pass.
5. A finite element analysis model shows that a litz wire coil without a coil case, directly buried (h=2cm) reinforced with resin, is seen to be integrated with the pavement by the resin,

and it is estimated that there is little deflection or distortion, and that it has high resistance to cracking and bending.

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