ASSESSMENT OF GROUTED GLASS FIBRE-REINFORCED POLYMER (GFRP) TUBES AS DOWEL BAR ALTERNATIVES

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ABSTRACT

The vast majority of highways and roads in China are made of jointed concrete pavement. The performance of concrete pavements depends to a large extent on the satisfactory performance of the joints. At present, the load-transfer devices used in China are almost all steel dowel bars. The new Chinese specification further emphasises the importance of dowels by stipulating that dowel bars be set in all highway jointed concrete pavements, increasing the diameter requirement and lowering the bar spacing, so the demand for steel is greatly increased. Currently, steel prices are increasing. With the international ironstone price rising by 70% last year, steel prices in China are likely to rise much higher, and the cost of civil engineering works using steel will also increase accordingly. Besides, steel dowel bars are susceptible to erosive agents. Moreover, the concentration of stresses occurs at the interfaces between the dowels and the supporting concrete because the stiffness of the steel is too great. Therefore, it is necessary to seek a substitute for steel dowel bars. Four grouted glass fibre-reinforced polymer (GFRP) tube dowels were compared with conventional steel dowel bars by means of laboratory experiments, theoretical analysis and finite element analysis. The research results revealed that grouted wound GFRP tube was a feasible substitute which could solve the problems posed by the currently used steel dowel bars, such as corrosion, excessive bearing stress and high cost. Finally, recommendations for further research on dowel bar alternatives are given.

Keywords: Dowel bar; Grouted GFRP tube; Load-transfer efficiency; Corrosion; Jointed concrete pavement; Bearing stress

1. INTRODUCTION

The vast majority of highways and roads in China are made of jointed concrete pavement. Concomitantly with the international rise in the mark-up on crude oil, the price of asphalt will rise accordingly. However, although most of the advanced asphalt is imported, China produces abundant cement. Therefore, jointed concrete pavements will be used to an even greater extent in new road construction.

Plain concrete pavements are greatly influenced by environmental factors such as temperature and humidity. Periodic temperature changes induce pavement stress, and cracking or spalling will occur when the stress exceeds the allowable criteria. Therefore, joints should be made to eliminate temperature stresses. However, joints create weak areas in the pavement. When load is applied to the joints, stress concentration occurs within both the slabs and the subgrades, which decreases the load-bearing ability of the pavement. As the Federal Highway Administration Advisory on concrete pavement joints (1990) explains: “The performance of concrete pavements depends to a large extent upon the satisfactory performance of the joints. Most jointed concrete pavement failures can be attributed to failures at the joint, as opposed to inadequate structural capacity.” Ideal joints must be relatively easy to install and repair, consolidate around the steel, provide adequate load transfer, seal the joint or provide for water migration, resist corrosion, open and close freely in temperature changes, enhance smoothness and low noise, and be aesthetically pleasing. Joint failure can worsen the working condition of slabs, which results in faulting, pumping, spalling, corner breaks, blowups and transverse cracking if lockup occurs.

The joints purposely create weak areas in the concrete and, therefore, require the use of load-transferring devices to maintain continuity in the pavement. According to an investigation report by AASHTO in 1993, pavement joints supported with dowels have a longer service life than joints without dowels.

At present, the load-transfer devices used in China are almost all steel dowel bars. The related new specification further emphasised the importance of dowels by stipulating that dowel bars must be set in all highway jointed concrete pavements, increasing the diameter requirement and lowering the dowel bar spacing, so the demand for steel is greatly increased. Currently, steel prices are increasing. With the international ironstone price rising by 70% last year, steel prices in China are likely to rise much higher, and the cost of civil engineering works using steel will also increase accordingly. Besides, steel dowel bars are susceptible to erosive agents. Moreover, the concentration of stresses occurs at the interfaces between the dowels and the supporting concrete because the stiffness of the steel is too great. Consequently, it is necessary to seek for a substitute material for steel dowel bars.

2. PROBLEMS INVOLVED IN THE USE OF CONVENTIONAL DOWEL BARS

China’s jointed concrete pavements are in serious need of repair. With some newly constructed roads, faulting and spalling occur extensively after only one year of traffic. An investigation revealed that the subgrade strength is sufficient, but a large factor in the deterioration of these roads is a result of how well the steel reinforcement transfers loads across the concrete slabs. Fabricating this reinforcement using a device conducive to transferring these loads will help to minimise roadway damage. The most common load-transfer device currently in use is the epoxy-coated steel dowel. The dowels present two main problems for the lifespan of the joint: loosening and corrosion within the joint.

Dowel bars are located at the joints and used to transfer load from one slab to its adjacent slabs. As long as the dowel bar is completely surrounded by concrete, no problems will occur. However, over time, traffic travelling over the joint may crush the concrete surrounding the dowel bar and cause voids due to excessive bearing stresses between the dowel and the surrounding concrete. Concrete crushing may occur due to stress concentration where the dowel contacts concrete at the joint face directly above and below the dowel. The high stresses weaken the concrete and eventually loosen the connection between the dowel and the pavement. Looseness of dowel support induced by concrete crushing can decrease the load-transfer efficiency across the joint and accelerate pavement damage (Friberg, 1940).

Besides, this void gives water and other particles a place to collect where it will eventually corrode and potentially bind or lock the joint so that no thermal expansion is allowed. Once load is no longer transferred across the joint, it is transferred to the foundation and differential settlement of the adjacent slabs will occur. Differential settlement of the slabs creates roughness at the joints, making vehicle travel uncomfortable and requiring that the slab be repaired or replaced.

Furthermore, since the dowels across a joint are exposed to environmental conditions, the dowels usually experience some corrosion, particularly in environments where salts are used for de-icing roads and highways in winter. Corrosion of the dowel bar can potentially bind or lock the joint. When locking of the joint takes place, no thermal expansion is allowed and new cracks parallel to the joint are formed directly behind the dowel bars in the concrete. As temperature decreases, contraction of the concrete widens the new cracks leading to reduction of load transfer. Once load-transfer efficiency decreases, differential settlement of the adjacent slabs will occur which leads to the need for slab repair or replacement. To minimise the problems caused by corrosion, epoxy-coated reinforcement is widely used. However, the effectiveness of the coating is highly dependent on whether it remains intact. The epoxy can chip off during placing or with wear during service and lose the ability to prevent the steel dowel bars from eroding. Therefore, some alternative dowel bar materials were considered. The dowel bar alternatives presented here as feasible substitutes should not only solve the above problems, but also be more cost-effective.

3. LITERATURE REVIEW

To solve the combination of the corrosion and bearing fatigue problems in dowel bars effectively, alternative materials to the conventional steel dowel were investigated. Khader Abu Al-eis (2003) tried to use MMFX corrosion-resistant steel dowel bars in place of conventional bars to prevent the bars from corroding. According to his research report, the highly corrosion-resistant MMFX steel has a low carbon content, less than 1%, and 8 to 10% chromium. It is uncoated and superior in strength to conventional steel. The Structural Laboratory of Iowa State University also considered copper and aluminum for dowels. However, the cost is likely to be much higher and excessive bearing stress at the bar-concrete interface still exists because the stiffness of MMFX steel is too high.

Oddem from the University of Minnesota tested grouted stainless steel tubes as dowel bars. The test results indicate that the use of 1.66-inch diameter, 1/8-inch thick-walled, 18-inch long, grouted stainless steel tube dowel bars may perform the same as the 1.5-inch diameter, 15-inch long, epoxy-coated mild steel dowels in retrofitted dowel bar installations. The test results also show that the performance measured in the grouted stainless steel dowelled specimen was slightly lower than that of the epoxy-coated steel dowelled specimen during the first 10 million applied load cycles. After this point, the stainless steel grouted tube specimen exhibited a rapid decrease in both load-transfer efficiency (LTE) and differential deflection. An internal examination was performed on the tested dowel bars, revealing that little deterioration in the grout had occurred. It is suggested that the type of grouted stainless steel tube dowels tested are capable of maintaining adequate, long-term load-transfer performance in the field. They are corrosion-resistant and not subject to the excessive bearing stress mentioned above.

Darren (1999) investigated the use of fibre-reinforced polymer (FRP) dowels for concrete pavements. It was shown that glass fibre-reinforced polymer (GFRP) dowels can be used in place of the standard steel dowels. Not only do the GFRP dowels transfer sufficient load to an adjacent slab, but they also do so over the service life of a highway pavement. Besides, GFRPs are a corrosion-resistant material that will require no maintenance during the life-span of the pavement. With continued research, full utilisation of corrosion-resistant load-transfer mechanisms could soon be standard practice in the pavement construction industry. Porter (2001) also conducted some research on FRP dowels, especially on the shape forms, including round, elliptical and hollow shapes.

Many researchers have concluded that GFRP dowels are a viable, corrosion-free alternative to steel dowels. Because the stiffness of GFRP dowels is close to that of the concrete slab, excessive bearing stress can be avoided. However, the high cost of the GFRP dowels in comparison with steel may suggest that their use as an alternative material may not be acceptable. Therefore, grouted GFRP tube dowels were investigated.

4. LABORATORY TESTS OF GROUTED GFRP TUBE DOWELS

4.1 General

GFRP tubes are extruded or wound with continuous glass filaments and polyester resin. Typically, filaments are drawn through a resin bath, sized by an appropriate die, to form the GFRP tube. An ultraviolet inhibitor is added to the resin to resist the effects of sunlight. The concrete will then be poured into the tube to form the dowel bar. The 28-day compressive strength of filled concrete is larger than 45 MPa. A extruded tube of one size and wound tubes of three sizes were utilised for the comparison with steel dowels. The length of the specimen was 250 mm.

4.2 Three-Point Bending Test and Double Shear Test

As this was not a standard three-point bending test, a clamp was specially designed for it (see Figure 1). The distance between two the fulcrums is 210 mm, and fulcrums were arc-shaped to prevent the tubes from sliding. Similarly, for the double shear test, a clamp was also specially designed (see Figure 2). A gap of 20 mm was left at each edge to avoid concentrating the stress.

Figure 1. Three-point bending test.

Figure 2. Double shear test clamp.

The widths of the press component and of the two supporting sleeves were all 70 mm and the gap between them was 1 mm. A hemispheroid concave dent was made at the top of the press component and a steel spherule was placed to prevent eccentric loading.

4.3 Test Results

Table 1 shows the results of the three-point bending test and the double shear test. From the table it can be seen that the shear strength of the grouted extruded GFRP tube is 165% higher than that of the tube alone, and, as for the grouted wound GFRP tubes, the range is from 100 to 143%. The strengths of the grouted extruded GFRP tubes are much lower than those of the wound ones. The results also showed that the grouted GFRP tube dowels exhibited lower shear strength and lower flexural moduli than the steel dowels. However, the load applied to a dowel was about 12 kN. Therefore, the strengths of the alternative dowels were higher than the actual stresses within the dowels induced by traffic loads.

Table 1. Results of the three-point bending test and double shear test.

Dowel type		Outside diameter (mm)	Inside diameter (mm)	Three-point bending load (kN)	Elastic modulus (MPa)	Shear strength (MPa)
Grouted wound GFRP tube	Dowel 1	66.0	50.0	93.4	4.2E+04	61.0
	Dowel 2	62.0	50.0	74.5	3.8E+04	56.0
	Dowel 3	59.0	50.0	57.4	3.5E+04	47.0
Grouted extruded GFRP tube	Dowel 4	50.0	45.0	13.6	1.9E+04	18.6
Steel		30.0	N/A	N/A	2.1E+05	117.0
Grouted wound GFRP tube	Tube 1	66.0	50.0	28.7	N/A	30.0
	Tube 2	62.0	50.0	19.2	N/A	26.0
	Tube 3	59.0	50.0	11.5	N/A	19.3
Grouted extruded GFRP tube	Tube 4	50.0	45.0	2.7	N/A	7.0

5. THEORETICAL ANALYSIS

5.1 Theoretical Model

According to Timoshenko's theory (1925), the deflection of a dowel bar within a pavement can be modelled as a beam on an elastic foundation:

$$-ky = EI\frac{d^4y}{dx^4} \tag{1}$$

where *k* = Modulus of foundation (MPa)

y = Vertical dowel deflection (cm)

E = Elastic modulus of dowel (MPa)

I = Moment of inertia of dowel (MPa)

By applying appropriate boundary conditions, the solution can be obtained as follows:

$$y = \frac{e^{-\beta x}}{2\beta^3 EI}[P\cos\beta x - \beta M_0(\cos\beta x - \sin\beta x)] \tag{2}$$

β = Relative stiffness of beam on foundation $= \sqrt[4]{k_0 b / 4EI}$ (3)

In order to calculate the deflection at the face, x is set as 0 to get the following:

$$y_0 = \frac{P_t}{4\beta^3 EI}(2+\beta z) \tag{4}$$

where k_0 = Modulus of dowel support (MPa/cm)

b = Dowel bar width (cm)

P_t = Load transferred by dowel (kN)

z = Joint width (cm)

5.2 Dowel Bar Deflection, Bearing Stress and Ultimate Bending Moment

For small joint widths, which is the case in this paper, deflections due to slope and flexure are very small. Therefore, the relative deflection across a pavement joint, Δl, can be expressed as follows:

$$\Delta l = 2y_0 + \delta \tag{5}$$

where δ = Shear deflection= $\frac{\lambda P_t z}{AG}$ (0.01 mm) (6)

λ = Form factor, equal to 10/9 for a solid circular section

A = Cross-sectional area of the dowel bar (cm^2)

G = Shear modulus (MPa)

Using the support modulus and the deflection at the face of the joint, the concrete bearing stress can be calculated as follows:

$$\delta_b = K_0 y_0 \tag{7}$$

The bearing stress defined by equation (7) should not exceed the allowable value. The following equation was given by the American Concrete Institute's (ACI) Committee 325 (1956):

$$\delta_a = (\frac{4 - b/2.54}{3}) f_c^{'} \tag{8}$$

where δ_a = Allowable bearing stress (MPa)

f_c' = Ultimate compressive strength of concrete slab (MPa).

The ultimate bending moment, *M_{max}*, induced by a wheel load can be calculated from Eq. (9):

$$M_{\max} = \frac{-P_t e^{-\beta x_m}}{2\beta}\sqrt{1+(1+\beta z)^2} \tag{9}$$

where x_m = Distance between the joint face and the location of $M_{max;}$ the relationship can be expressed by the following:

$$Tan(\beta x_m) = \frac{1}{1+\beta z} \tag{10}$$

5.3 Defining Load Transfer

5.3.1 Load-transfer efficiency

Load-transfer efficiency (LTE) is defined as "the ability of a joint or crack to transfer load from one side of the joint or crack to the other". LTE can be quantified in several ways. The three equations most extensively used for calculating LTE are:

$$LTE = \frac{\Delta_U}{\Delta_L} \times 100\% \tag{11}$$

$$LTE = \frac{2\Delta_U}{\Delta_L + \Delta_U} \times 100\% \tag{12}$$

$$LTE = \frac{\sigma_U}{\sigma_L} \times 100\% \tag{13}$$

where Δ_U = Deflection of the unloaded slab (0.01 mm)

Δ_L = Deflection of loaded slab (0.01 mm)

σ_U = Stress in unloaded slab (MPa

σ_L = Stress in loaded slab (MPa)

Equation (11) is the most widely accepted method of determining LTE, and therefore it was adopted for the LTE calculations here. Load-transfer efficiencies between 70 and 100% are considered as good load transfer, and 80% is an excellent criterion in Chinese specifications. However, in rehabilitation projects, LTE values between 90 and 100% should be expected if retrofitting procedures are carefully followed. LTE values below 50% often result in pavement problems similar to those found in joints or cracks containing no load-transfer devices.

5.3.2 Differential deflection

Differential deflection is the difference in vertical movement between the loaded and unloaded portions of a pavement at a discontinuity. Measuring the differential deflection between adjacent slabs is a good way to provide further information about the load-transfer efficiency of a pavement joint or crack. Differential deflection, ΔD, can be calculated from Equation (14):

$$\Delta D = \Delta_L - \Delta_U \tag{14}$$

where Δ_L = Deflection of loaded slab (0.01 mm)

Δ_U = Deflection of the unloaded slab (0.01 mm)

LTE does not take into account the magnitudes of deflections. Therefore, it is necessary to measure the differential deflection for better understanding of LTE effectiveness. Different magnitudes of differential deflections can result in the same LTE value since LTE is simply a ratio of the deflections measured on the loaded and unloaded sides of a joint. Therefore, it is important to look at the differential deflections of adjacent slabs, in conjunction with LTE values, to determine the ability of a joint to transfer vertical shear forces.

5.4 Results of the Theoretical Analysis

Based on the theory given above, theoretical calculations can be made. The parameters are listed in Table 2.

Table 2. Calculation parameters.

Slab thickness	Joint width	Dowel spacing	Applied load	Subgrade reaction (K)	Dowel support (K_0)
26 cm	1 cm	30 cm	50 kN	110 MPa	4.0E+03 (MPa/cm)

The theoretical calculation results, provided in Table 3, showed that the dowel-concrete bearing stresses were all lower than the allowable bearing stresses. In the case of Dowel 1, Dowel 2 and Dowel 3, the deflections were all lower than those with steel dowel bars and there was not much difference between the ultimate bending moments induced by traffic loads. However, Dowel 4 had a relatively larger deflection and bearing stress.

Table 3. Results of the theoretical analysis.

Dowel type	y_0 (0.01 mm)	δ (0.01 mm)	Δ (0.01 mm)	$δ_b$ (MPa)	$δ_a$ (MPa)	M_{max} (N.m)
Dowel 1	2.0	0.4	4.4	8.1	18.7	229.0
Dowel 2	2.3	0.5	5.1	9.3	20.8	216.0
Dowel 3	2.6	1.0	5.8	10.4	22.4	206.4
Dowel 4	4.1	2.5	10.8	16.8	27.1	166.7
Steel	4.8	0.2	9.8	19.5	36.5	204.5

6. FINITE ELEMENT ANALYSIS

For a comparison with the theoretical results, finite element analysis was used (see Table 4). The finite element model was also a good way of calculating the internal stresses in the dowel and pavement slab that cannot be determined easily through theoretical analysis. The dowel bar system was modelled as a beam on an elastic foundation. Solid and beam elements were used, and coupling had to be done because they had different degrees of freedom. The parameters used for finite element analysis were determined to correspond to those values in Table 2 that provided useful comparisons.

Table 4. Results of the finite element analysis.

Dowel type	$δ_b$ (MPa)	y_0 (0.01 mm)	M_{max} (N.m)	ΔD (0.01 mm)	LTE(%)
Dowel 1	9.7	2.4	241.0	0.11	97.5
Dowel 2	10.5	2.7	224.1	0.17	95.7
Dowel 3	11.2	3.2	218.7	0.21	92.4
Dowel 4	17.9	4.8	182.5	0.87	78.3
Steel	21.6	5.2	227.6	0.28	94.6

As shown in Table 4, Dowel 4 had a large differential deflection and a very low LTE. However, the rest of the alternative dowel bars had smaller differential deflections than the steel dowels and there was not much difference between their LTEs. The bearing stresses and ultimate bending moments computed with finite element analysis were close to those calculated by the theoretical analysis.

7. ECONOMIC ANALYSIS

The use of grouted GFRP tubes could provide a feasible solution to the deterioration of concrete pavement joints currently caused by the corrosion of steel dowels and simultaneously decrease the bearing stresses around the dowel-concrete interface. Nevertheless, cost-effectiveness is important when an application is considered. Table 5 compares the initial costs of five different materials. The table shows that the grouted wound GFRP tube is about 16 – 30% cheaper than steel dowels, and besides, if grouted GFRP tubes were used for dowels, corrosion would not occur and they could extend the lifetime of the pavement without requiring repairs. However, the use of steel dowels typically causes corrosion and they require replacement during the useful life of a concrete pavement. If a life-cycle cost analysis was done, grouted GFRP should be found to be much cheaper than steel dowel bars. Therefore, the cost-effectiveness of grouted GFRP suggests that their use as alternative dowels may be acceptable.

Table 5. Initial costs of five alternative dowel materials.

Dowel type	Dowel 1	Dowel 2	Dowel 3	Dowel 4	Steel	Epoxy-coated steel
Cost per dowel (RMB)	22.53	21.60	18.00	12.86	21.95	26.80
Cost per dowel (US$)	2.78	2.66	2.22	1.59	2.71	3.30

8. CONCLUSIONS AND RECOMMENDATIONS

Grouted GFRP tube dowels were generally found to have adequate strengths and low differential deflections, except for grouted pultruded GFRP tubes (Dowel 4). The LTEs of grouted wound GFRP tube dowels are comparable to steel dowel bars, provided the diameter of the grouted GFRP dowel is larger than that of the steel dowel. The larger diameter results in a reduction in bearing stresses that, in turn, reduces the potential for faulting. Besides, the smooth outer surface of GFRP tubes eliminates the need to apply de-bonding agents prior to paving to prevent the dowel from locking in the joint, which is more convenient for construction and also decreases the cost. Grouted wound GFRP tube dowel bars can prevent corrosion, avoid excessive bearing stress around the concrete-dowel interface and have economic advantages. In conclusion, grouted wound GFRP tubes are feasible alternative materials in place of the currently used steel dowel bars.

Suggestions for further research are as follows:

(1) If resources permit, an evaluation of filled grouted GFRP tube dowels and accelerated corrosion testing should be conducted in the future.
(2) Grouted GFRP dowels with elliptical or I-beam cross-sections should be investigated in order to further decrease the bearing stresses.
(3) Other GFRP tubes that have higher strengths should be investigated for their potential use as dowels. By using a stronger resin or glass fibres with higher tensile strength, the shear behaviour can be greatly improved. These types of grouted GFRP tube dowels may be more suitable.
(4) The feasibility of industrial-scale production should be investigated as they may be preferable for concrete pavement construction.
(5) The current guidelines for steel dowel bars may be not suitable for grouted GFRP tube dowels. The relationship between pavement thickness and dowel diameter should be investigated for grouted GFRP tube dowels, and optimal bar spacing, length, diameter and joint width should also be determined.

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