Experimental investigation on the combined effect of dowel misalignment and cyclic wheel loading on dowel bar performance in JPCP

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Abstract

A number of previous studies indicated that the joint lockup due to misalignment and looseness of dowel bars may cause joint distress in Jointed Plain Concrete Pavement (JPCP). This article reports a detailed experimental investigation of pull-out load and joint lockup due to dowel misalignment; and dowel looseness caused by the combined effect of misalignment and cyclic traffic load. The test slabs were supported on steel beams with an appropriate amount of vertical stiffness so as to incorporate the effects of underlying layers of real pavements. The article also provides an experimental investigation to assess the suitability of Glass Fibre Reinforced Polymer (GFRP) bars as alternative dowel bars to reduce joint lockup and associated detrimental effects at the dowel-concrete interface compared with epoxy-coated steel dowels. The results show that the 38 mm GFRP dowels that have equivalent flexural rigidity (EI) to 25 mm steel dowels can withstand the cyclic traffic load, significantly reduce joint lockup and dowel looseness, and can provide adequate Load Transfer Efficiency (LTE). It was also observed that misalignment affects dowel looseness significantly more than the number of cycles for traffic load. The slab-base separation and orientation of misaligned dowels have significant effects on the load required to open the joint.

Keywords	Experimental test; Dowel misalignment; GFRP; Dowel bars; Load Transfer Efficiency (LTE);Dowel looseness; Relative Deflection (RD).
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Highlights

- Experiments to assess the suitability of GFRP as alternative to steel dowels in JPCP
- Investigate the effect of dowel misalignment under realistic pavement representation
- The results show a better overall performance of 38 mm GFRP dowels compared to 25 mm steel dowels with equivalent flexural rigidity (EI).
- GFRP dowels significantly reduce joint lockup and dowel looseness
- Misalignment magnitude and orientations affect pull-out load considerably

Experimental investigation on the combined effect of dowel misalignment and cyclic wheel loading on dowel bar performance in JPCP

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ABSTRACT

A number of previous studies indicated that the joint lockup due to misalignment and looseness of dowel bars may cause joint distress in Jointed Plain Concrete Pavement (JPCP). This article reports a detailed experimental investigation of pull-out load and joint lockup due to dowel misalignment; and dowel looseness caused by the combined effect of misalignment and cyclic traffic load. The test slabs were supported on steel beams with an appropriate amount of vertical stiffness so as to incorporate the effects of underlying layers of real pavements. The article also provides an experimental investigation to assess the suitability of Glass Fibre Reinforced Polymer (GFRP) bars as alternative dowel bars to reduce joint lockup and associated detrimental effects at the dowel-concrete interface compared with epoxy-coated steel dowels. The results show that the 38 mm GFRP dowels that have equivalent flexural rigidity (EI) to 25 mm steel dowels can withstand the cyclic traffic load, significantly reduce joint lockup and dowel looseness, and can provide adequate Load Transfer Efficiency (LTE). It was also observed that misalignment affects dowel looseness

significantly more than the number of cycles for traffic load. The slab-base separation and orientation of misaligned dowels have significant effects on the load required to open the joint.

Key words: Experimental test; Dowel misalignment; GFRP; Dowel bars; Load Transfer Efficiency (LTE);Dowel looseness; Relative Deflection (RD).

INTRODUCTION

Concrete pavements suffer several types of volumetric changes and stresses after casting due to thermal expansion or contraction, and concrete shrinkage. The transverse joints are introduced to relieve these stresses. Almost all highway agencies around the world recommend using dowel bars to transfer the load across the joints and to reduce the relative deflection (RD) of the pavements.

Many concrete pavement problems come from joint distress[1]. Dowel looseness and dowel misalignment are two important sources of joint distress. These two phenomena have been investigated previously in isolation. Dowel looseness is an enlargement of the dowel bar socket that usually occurs due to repeated traffic load, wearing or corrosion of steel dowel bars[2]. Dowel misalignment occurs during the construction process of the joints when the dowel bars are misplaced in positions and/or orientations. The misaligned dowels restrain the slab movement by locking the transverse joints; this may initiate mid-span cracks, breakage of the corners of slabs and joint spalling [3].

Dowel misalignment can be classified into two types: (a) translational misalignment, which occurs when the whole dowel bar is offset from the central plane of the concrete slab in any direction (horizontally, vertically or longitudinally) but it remains parallel to the centreline of pavement; (b) skew (rotational) misalignment, which occurs when the centroid of the dowel is in the correct position but the dowel tilts horizontally or vertically or in both directions [4]. In practice, a particular dowel bar set may contain both types of misalignment. The focus of this study is on the

1 skew (rotational) misalignments since they lead to more restraint to the slab movement, and as a
2 result have more detrimental effect than the translational misalignments [4, 5] (see Fig.1 for some
3 types of skew misalignments).

4 The current article presents a detailed experimental investigation into the evaluation of dowel bars'
5 performance when they are subjected to the combined effect of wheel load and misalignment issues.

6 The study also evaluates the suitability of GFRP dowel bars in those problem scenarios as
7 alternative to steel dowels. GFRP is a corrosion free material and possesses low coefficient of
8 friction which may reduce joint lock-up. The experimental programme also addressed the effect of
9 vertical stiffness of the underlying layers of pavement which had been omitted in most of the
10 previous tests [3, 5, 6].

11 **PREVIOUS STUDIES**

12 There are limited number of studies on the effects of dowel misalignment in the literature,
13 considering its huge detrimental effects on joints and pavement performance. Most of the previous
14 investigations focused on the determination of magnitude and types of misalignment that would
15 cause joint distress [7, 8]. Segner and Cobb (1967) tested concrete pavement sections of 1.83 m (6
16 ft) wide, 1.68 m (5.5 ft) long and 0.25 m (10 in) thick. Their results showed that the load required to
17 open the joint increased noticeably for the misalignment magnitude greater than 6.4 mm compared
18 with aligned dowels.

19 Tayabji (1986) carried out laboratory tests on slab sections of 0.92 m (3ft) wide, 2.1 m (7ft) long
20 and 0.2 m, 0.25 m (8 in, 10 in) thick with sets of one and two dowels. The tests involved
21 misalignment levels of 0, 3.2, 6.4, 12.7, 25.4 and 50.8 mm per half-length of dowel (225 mm). The
22 results showed no significant difference in pull-out load for single misaligned dowel specimens,
23 whereas a significant increase in pull-out load was observed for the specimens containing two

misaligned dowels when the misalignment magnitude exceeded 12.7 mm per half dowel length. It should be noted that there are multiple dowels bars along a typical transverse joint and the interaction effect during pull-out can not be ignored [9].

Prabhu et al. [5, 10, 11] carried out experimental as well as numerical investigations to produce guidelines for allowable dowel misalignment. Their investigations involved one, two, three and five 32 mm diameter steel dowel bars with different misalignment magnitudes (0, 6.35, 12.7, 19, and 25.4 mm per half-length of the dowel bar) and different misalignment types (vertical, horizontal and combined). The results showed that all joints in a concrete pavement start initial slipping when the load per dowel exceeds 5 to 7 kN. They also concluded that in general the joint-opening load per dowel increases for an increase in the magnitude and non-uniformity of dowel misalignment. However, in their test arrangement the slabs were fixed to the foundation, restricting any separation between the slab and the bottom layer of pavement that may happen in reality during an event of joint opening or closing. For this reason, there was insignificant difference between the loads required to open the joint for vertical and horizontal misalignments. The current set of experiments was designed by allowing for possible base separation and the effect it may have on the pull-out load.

Hoegh and Khazanovich recently carried out experimental and numerical investigations to study the effect of dowel misalignment on LTE [6, 12]. The test consisted of a concrete beam ($457 \times 1200 \times 203$ mm) fitted with four 38 mm round steel dowel bars (greased and ungreased). Each bar was 457 mm long, of which 229 mm was embedded in concrete with different levels of misalignment. The dowels were pulled out individually in the longitudinal direction for 6.4 mm (0.25 inch) and the pull-out force versus displacement was recorded. The shear capacity of the dowel bar was evaluated by turning the beam on its side and applying direct shear on the non-embedded part of the dowels. Their results suggested that dowel misalignment has an insignificant effect on the pull-out load required to open the joint [6, 12]. Since the test arrangement is similar to

1 a direct pull-out test for individual dowels, no interaction among the misaligned dowel bars was
2 possible. Hence the test arrangement was not representative of actual slab-openings in the field.
3 Also, the casting of the specimens in a vertical direction may have reduced the variations in
4 shrinkage strains for different dowel orientations[13, 14], which is an important factor in the
5 development of bond strength. The test arrangement excluded the possibility of additional bearing
6 stress arising due to constrained movement of the adjacent dowels. However for higher
7 misalignment magnitude, the results showed lower shear capacity for the dowel bar and more
8 deterioration of the surrounding concrete.

9 GFRP dowels as a non-corrodible dowel bars can be considered as a practical alternative to steel
10 dowel bars in JPCP especially in harsh environmental conditions. Several studies have been
11 conducted on GFRP dowels as load transfer devices in concrete pavements [15-18]. These studies
12 investigated, both experimentally and theoretically, JPCP with GFRP dowels for static and cyclic
13 load. Their results found that the GFRP dowels are adequate as load transfer devices when proper
14 diameter and spacing are selected. The authors recently published two articles (experimental study
15 and numerical simulation) evaluating the performance of GFRP dowel bars in JPCP and provided a
16 design consideration guideline [19, 20]. The experimental results showed that GFRP dowels can
17 perform similar to steel dowels if they have equivalent flexural rigidity (EI). The Numerical results
18 investigated the magnitude and distribution of bearing stress underneath both types of dowels for
19 various pavement system parameters. It should be noted here that a couple of previous studies
20 reported that the GFRP bars being highly water absorbent may cause an increase in bar diameter
21 and degradation in mechanical properties [21, 22]. However, an experimental programme that had
22 been conducted on GFRP dowels taken from a pavement section constructed by the Ohio
23 Department of Transportation and Civil Engineering (after 15 years of field service) demonstrated
24 that the dowels had been virtually unaffected with no significant decrease in mechanical properties
25 [23]. Robert et al. [24] carried out a durability test of GFRP dowels by measuring their mechanical

properties after immersing in water at 60°C for 75 days. The results showed that the aging process produced an insignificant effect on the shear and flexural strengths. Other durability investigation [25] on GFRP dowels showed a superior long term performance for vinylester-based GFRP dowels (used in this study) compared to the polyester-based ones.

In summary, there is a clear need to study the effect of cyclic traffic loading on misaligned dowel-pavement system, and to assess any increase in dowel looseness and reduction in Load Transfer Efficiency (LTE), which has not been addressed before. Experiments with single misaligned dowel bars do not include important interactions between the dowels in a real pavement. Besides the magnitude and type of misalignment, the stiffness of the experimental slabs in the vertical direction is an important aspect to consider. Also allowing the slab to separate from the base would have markedly different effects on vertical misalignment compared to horizontal misalignment. This aspect has not been considered adequately in previous studies. Finally, the use of GFRP dowels has been reported in the literature, primarily for their non-corrodible properties. However a very limited amount of research has been published on the effect of misalignment of GFRP dowels and how do they compare with the misaligned steel dowels of equivalent flexural rigidity.

EXPERIMENTAL SETUP

The experimental work was conducted in the Heavy Structures Laboratory of University of Manchester [26]. Eight specimens were tested, six of which were fitted with GFRP dowels and two were fitted with epoxy-coated steel dowels (see Table 1 for details). Each test specimen consisted of two concrete slabs connected by steel or GFRP dowel bars. These two slabs were separated by 3 mm smooth steel plate during the concrete casting. Appropriate holes and slots were made in the separation plate to allow for the dowels to connect the slabs across the joint and also to facilitate the

removal of the plate itself after the following day of casting. The dimensions of the slabs were 900 mm × 900 mm × 200 mm for specimens containing two dowel bars and 900 mm × 1200 mm × 200 mm for the specimens containing three dowel bars. The dowel bars used in the test were of two types: (a) 25 mm diameter, round, smooth, fully epoxy-coated steel bars for which one half of the length was greased as well; and (b) 38 mm GFRP dowels. All the dowels were 458 mm long. These dowels were embedded for equal lengths (227.5 mm) on each side of the joint. The thickness of the slabs and the dimensions of the steel dowels were selected according to the general guideline of AASHTO (1993). The diameter of the GFRP dowels was chosen to get an equivalent flexural rigidity (EI) to the steel dowel bars. The tests have been carried out for the slabs having two and three dowel bars to incorporate the effect of adjacent dowels.

The concrete mix design was carried out following the methods of normal concrete mix design outlined in [27]. The mix ratio (cement: fine aggregate: coarse aggregate) was 1:1.5:2.6 and water/cement ratio of 0.55. This mix design was for a nominal concrete compressive strength of 28 MPa at 28 days. However, the average measured concrete compressive strength was 33 MPa at 28 days.

The slab-moulds were manufactured with 18 mm thick plywood except for the cut boxes' sides which were of 36 mm thick plywood (see Fig.2). Cut boxes were made at both sides of the mould to make grooves to hold the hydraulic jacks while pushing the slab apart to create the required joint opening. Four other hydraulic jacks were inserted between the frame of the machine and the slabs to push back the slabs during the closing of the joint. Small grooves were also made at the base and sides of the mould to fix the 3 mm thick separating plate. The slots in the separating plate beneath the dowels were closed using sticky plastic tape before pouring concrete. The plate was kept in the specimens until the concrete initially set and then it was removed (next day) by carefully pulling it in vertical direction. The sticky tape underneath the dowels was later removed when the slab was being lifted for testing.

1 The dowel bars were held at their positions at the mid-depth of the specimen at a spacing of
2 300 mm before and during the casting process using 8 mm diameter smooth steel bars with 40 mm
3 threaded ends. Both ends of each dowel bar were drilled and threaded to 40 mm. The steel bars
4 were connected to the ends of the dowel bars and to the holes at the sides of the mould (see Fig.2).
5 These bars were coated with thick layer of grease so that they could be easily removed from the
6 specimens on the day following the casting of the concrete. To achieve the required misalignment
7 magnitude and orientation, holes were drilled at appropriate locations on the sides of the mould that
8 held the steel bars in place. The misalignment magnitude and orientation were checked after
9 installing the dowels and before casting.

10 In order to consider the case of an actual pavement resting on the ground, a supporting base-system
11 with equivalent foundation stiffness for the test slab was designed (see Fig.3).This consisted of four
12 transverse beams simply supported on two longitudinal beams (see Fig. 3(c)) resting on a strong
13 floor in the Heavy Structures Laboratory. The supporting beams were designed using two sets of
14 Finite Element (FE) analyses to represent a base layer with subgrade reaction modulus (stiffness) of
15 54 MN/m^3 [28]. In the first FE analysis, the test slab was supported by an elastic foundation which
16 also allowed any slab-base separation. In the second FE analysis the test slab was supported by four
17 beams with the arrangements shown in Fig. 3(c); interactions between the slab and the transverse
18 beams were modelled by surface to surface contact. The dimensions of the beams were selected
19 such that the deflections of the slabs at eight LVDT positions (Fig. 4) and the shear force and
20 bending moment in the dowels would be of similar values in both the analyses. Subsequently, the
21 second FE model was checked using the displacement values from the experiments. The interior
22 beams were UB $127 \times 76 \times 13$ while the outer beams were UB $152 \times 89 \times 16$. The clear length of
23 these beams was 2000 mm. These long beams acted as equivalent spring supports underneath the
24 specimen. A similar arrangement was found in literature in evaluation of load transfer mechanism
25 [2, 15]. To minimize the effect of friction between the steel base and concrete slab on the load

1 required to open the joint, a 1.5 mm thick layer of Polytetrafluoroethylene (PTFE) was used
2 underneath and on the sides of the slabs. Any in-plane rotation that may have occurred during the
3 slab movement was prevented by clamping the slabs as shown in Fig. 3. This base arrangement
4 allowed slab-base separation during the slab movement. The amount of separation that may have
5 occurred depends on the orientation of the misaligned dowel bars.

6 In order to achieve the objectives of the current study, different types and magnitudes of
7 misalignment were considered. These cases involved aligned dowels as well as vertically non-
8 uniform, horizontally non-uniform, and partially misaligned dowels (see Fig. 1). Three values of
9 misalignment were chosen: zero misalignment, 12.5 mm and 25 mm per half-length of the dowel
10 bar (see Table 1). The first value was selected to represent the typical installation of aligned dowel
11 bars at the transverse joints without any construction error. The second value was adopted to
12 represent misalignment magnitude more than the permissible limits according to the most highways
13 agencies [29]. Also, this selection was made to keep the distress surrounding the dowel bar
14 localized without significant cracking during opening of the joint by 12 mm [10] to allow for the
15 evaluation of LTE under cyclic load, after the slabs were pulled out and pushed back representing
16 slab movement. Previous studies [5, 10, 11] showed that 12.5 mm misalignment (per half-length of
17 the dowel) did not cause global failure of specimen. The third value of misalignment magnitude (25
18 mm) was adopted to investigate the effect of high misalignment magnitude as well as failure
19 mechanism of the specimens due to joint lockup.

20 Although the 12 mm joint opening that has been considered in the tests is greater than the typical
21 movement of joints (6.4 mm) in JPCP [30], this may occur due to construction of long slabs or
22 locking up of some joints. For a particular slab, this high level of opening (12 mm) represents the
23 worst case combined scenario of concrete contraction due to extreme temperature variation,
24 concrete shrinkage (as a result of high water content, or poor aggregate gradation, or using certain

types of additives). Keeping that in mind, comparisons were also made at joint opening of 3 mm and 6 mm.

Test sequence

The experimental programme was conducted in four major steps as follow:

1. Step one involved deflection measurement under a static wheel load of 40 kN. This load is equivalent to a single axle load according to the AASHTO [30] guide and BS 7533-12[31].
2. The second step consisted of recording the load required to open the joint by 12 mm when the slabs were pushed apart by two hydraulic jacks, and then pushed back to the original position.
3. The third step involved repeating the deflection measurement similar to that taken in Step one under a static wheel load of 40 kN.
4. The fourth step involved applying the 40 kN load for one million cycles to compare the effect of the cyclic wheel load on the GFRP dowels with that of the steel dowel bars and also the effects of dowel misalignment and joint lockup on the long term performance for both types of dowel.

The specimens were instrumented as shown in Fig.3 and Fig.4. The vertical deflections of the specimens were measured using LVDTs at 8 locations in two rows parallel to the dowel bar centre line as shown in Fig.4. The testing machine consisted of two controlled loading actuators held by transverse beams connected to the machine frame. A thick steel plate 200 mm× 345 mm × 40 mm was attached to each actuator in order to apply the 40 kN load as a dual wheel load of single equivalent axle load. The dimensions of the loaded area were selected to produce a tyre inflation pressure of 580 KPa as recommended by Huang[32].

The static load was applied on one side of the slab monotonically from 0.5 kN to 40.5 kN while the other side was clamped by the second actuator which applied a nominal 0.5 kN load on the unloaded side of the specimen to prevent any possible upward movement. The deflection data for

the slab were recorded during the load application. The relative deflections of the joint faces were calculated and then the LTE and the dowel looseness were computed from the deflection values.

The concrete slabs involved in the current experimental programme were fitted with steel and GFRP dowel bars with different orientations, misalignment types and misalignment magnitudes, and with different numbers of dowels in the specimens. The two halves of the specimens were pushed apart using two hydraulic jacks connected to one main pump to create a 12 mm additional joint opening. These jacks applied the load as pressure on the steel plates attached to the specimen's sides in order to distribute the load on them. The loading rate was 0.5 mm/min. The load required to open the joint was recorded during this step. The load created by each jack was measured using load cells attached to the jack, while the joint opening was measured using two horizontal slider LVDTs attached to the top surface of the specimens as shown in Fig.3 and Fig.4. After measuring the load required to open the joint, the slabs were pushed back to maintain the initial joint opening by inserting a 3 mm thick separator plate which was used during casting. The relative deflection (RD) of the joint was measured again under the same static load (40 kN) to show the effect of dowel misalignment and joint lockup on dowel looseness and LTE. Since any increase in RD is most likely related to the deterioration of concrete pavement system behaviour around the dowel, the dowel looseness was assumed to be equal to the increase in RD before and after the slab movement[15].

Since a slab movement occurs immediately after concrete casting due to concrete shrinkage and changes in hydration temperature (before opening a road to traffic), this movement was applied in the test specimens before starting the cyclic load test. Although the expansion and contraction of slabs are a continuous process during a pavement's life, in the experimental programme it was carried out only once at the start, since the objective of the study was to obtain a clear picture of the difference between the looseness due to slab movement and the looseness generated due to cyclic load.

The last step of the test included an evaluation of the long term performance of GFRP and steel dowel bars in JPCP under cyclic load. The combined effect of dowel looseness due to slab movement (representation of thermal movement and shrinkage) and cyclic load (representation of repeated traffic load) on LTE was investigated in this step. The cyclic load was applied as a sinusoidal function on both the slabs in order to represent truck wheel load passing the joint. The load amplitudes ranged between 0.5 - 40.5 kN and the frequency of the load application was 4 Hz. The load from either actuator was out-of-phase to each other, i.e., when one actuator was providing a full load of 40.5 kN, the other actuator was providing 0.5 kN. The lower limit was set to 0.5 kN so that the actuator would restrain any upward movement. The upward movement in a real slab would be counteracted by its self-weight, the effect of which is much lower for this scaled down test specimen. A rubber pad of 1 mm thickness was placed beneath each load actuator to prevent any crushing of concrete during the cyclic load and to produce a more realistic load distribution. Deflections of the concrete slabs were measured under 40 kN static load after (i) 250,000 (ii) 500,000 (iii) 750,000 and (iv) 1 million cycles of the applied 40 kN load. All test process started after 28 days of casting the concrete slabs.

RESULTS AND DISCUSSIONS

Firstly, the present set of experimental results considered appropriate foundation stiffness while assessing the effect of dowel misalignment. In previous experiments reported in the literature, the effects of the underlying layers have been completely ignored. The supporting base for the slabs was designed to mimic the underlying layers. Secondly, the suitability of GFRP dowels was tested for whether they could reduce the required pull-out load compared to the steel dowels. Finally, the results of the combined effect of dowel misalignment and traffic wheels' load on dowel looseness and LTE are presented.

Dowel Misalignment for GFRP and steel dowel bars

According to the standard pull-out load versus joint opening behaviour, debonding of the dowel bars from a concrete pavement consists of two parts[11, 33]: (i) fully bonded to initial splitting part; in which, the dowels are assumed fully bonded until the start of the initial slipping. The behaviour during this stage is governed by the bond strength between the dowel bar and the concrete pavement surrounding it, as represented by Eq.1. This equation assumes uniform bond along the whole embedded length of the dowel which is not the case in practice. It has been used here nevertheless as a comparison tool. Part(ii) slipping region, represents the de-bonding region which starts after initial slipping. Slipping of the dowel bar starts when the dowel-concrete interface shear exceeds the bond strength between the dowel bar and the surrounding concrete.

$$\tau = \frac{F}{\pi DL} \quad (1)$$

Where:

τ : bond stress,

F : load per dowel bar,

D : diameter of dowel,

L : length of dowel bar.

Even for the epoxy-coated steel dowel bars which are designed to have no bond with concrete pavement, a small amount of bond exists due to chemical adhesion between the dowel bars and the concrete, and the frictional stress due to wearing or nicking of the dowel bar coating. Unlike the standard pull-out tests where the load drops significantly when the bond strength has been fully mobilised, the slipping region for a slab-dowel system is characterised by the transverse interaction between the dowel bars and the surrounding concrete arising from the displacement due to slab self-weight. If there are multiple dowels across the joint, any non-uniformity in slab movement or misalignment of dowels would create additional bearing stress on the concrete[34].

Two misaligned dowels

Figs.5 to 8 illustrate the pull-out loads required to open the joint for different cases of dowel misalignment for GFRP and epoxy-coated steel bars. The general observations obtained from these figures are that any dowel misalignment produces an increase in pull-out load, and the initial slipping of the steel bars starts at a lower load compared to the GFRP dowels (see Figs.6 and 8). The load required for initial slipping is governed by the bond strength between the dowel bar and concrete. For similar bond strength the load required for initial slipping increases with higher diameter as given by Eq.1. The initial slipping was considered to take place at 0.05 mm joint opening. Also this was the smallest measured displacement achieved by the slider LVDTs with a high level of certainty in the experimental test. The initial slipping of the aligned steel dowel bars occurred at 2.5 kN while for the GFRP it occurred at 4 kN, which is approximately at a similar ratio of the diameters. The initial slip load value of steel dowels is comparable to what had been observed in the literature[5].

Fig.5 shows the effect of vertical misalignment for the GFRP dowels (GA2 and GV2N2). The results indicate that there is no significant difference between the specimens with aligned (GA2) and misaligned dowels (GV2N2). The maximum load required to open the joint for specimen GA2 is 8.35 kN while for the specimen GV2N2 it is 8.85 kN after initial slipping. Both specimens exhibited similar behaviour at the post initial-slipping stage. The load required to open the joint did not change significantly at this stage for both the specimens. It showed a decreasing trend during the opening of the joint where the final values at the 12 mm joint opening were 7.1 kN and 7.5 kN for the specimens GA2 and GV2N2 respectively. This small difference can be explained by the fact that, for non-uniform vertically misaligned dowels, part of the pulling force will be expended as bearing pressure on to the dowels, which will eventually require a higher pull-out force for the same amount of slip. The load-slip behaviour for the misaligned specimen was relatively smooth possibly due to the relative vertical positions of the slabs at the joint being maintained by two non-uniformly

1 misaligned dowels creating two opposing wedge effects. For the aligned specimen, the zigzag
2 profile can be attributed to possible stick-slip behaviour.

3 Fig.6 shows pull-out load versus joint opening for aligned GFRP and steel dowels. The graphs show
4 that, for the steel dowel bars (SA2) slip initiates at a lower load level of 2.5 kN than that of the
5 GFRP dowels (GA2) at 4 kN due to smaller contact area according to the bond stress formula
6 (Eq.1), assuming similar level of initial bond strength. The post initial-slip load for steel dowels
7 increased until it reaches a maximum value of 10.8 kN at a joint opening of around 4 mm. After
8 initial slipping (2.5 kN), the behaviour was governed by interlock friction resulting from the layer
9 of mortar sticking to the dowel surface as observed in the post-mortem of the specimens. It is also
10 to be noted that strain compatibility along the length of a dowel would dictate that the breaking of
11 bond does not occur at a single instant, rather it progresses from one end. The post-initial slip
12 behaviour for the GFRP dowels (from 4 kN to the maximum of 8.35 kN) on the other hand, was
13 less gradual as the progression of bond-breaking may have occurred at a higher rate due to smoother
14 surface profile at micro-scale. The pull-out load increases until complete breaking of the entire
15 bond. For the steel dowels this occurs at around 4 mm of joint opening, and the pull-out load starts
16 to decrease hence forth due to lower friction coefficient arising from smoothing of the dowel-
17 concrete interface layer with increasing slip. For the GFRP dowels, there was no evidence of layer
18 of cement mortar sticking to the dowel surface. As a result, the last stage of the load slip behaviour
19 did not involve further smoothing of the interface layer for increasing joint-opening.

20 Fig.7 illustrates the comparison of load-slip behaviour for aligned and vertically misaligned steel
21 dowel bars (SA2 and SV2N2). Although, the misalignment of steel dowel bars and its effect on
22 pull-out load and stress at the dowel-concrete interface had been investigated in literature, the
23 combined effect of cyclic wheel load and dowel misalignment on the performance of the dowel-
24 joint system has not yet been explored. Also, most of the experimental programme in literature did
25 not incorporate the effect of stiffness of the base layer. Therefore, an understanding of the effect of

dowel misalignment is somewhat incomplete. The testing of these specimens (SA2 and SV2N2) was carried out with the aim of providing a clearer picture of steel dowel-concrete slab interaction and to give a better understanding of the effect of dowel misalignment. These tests were also used to investigate the detrimental effect of misalignment for GFRP dowels and a comparison was made with the steel dowels (SA2 and SV2N2) of equivalent flexural rigidity.

The results showed a significant increase in the load per dowel required to open the joints of vertically non-uniform misaligned steel dowels (SV2N2) compared with the aligned dowels (SA2). The maximum load observed for SV2N2 was about 14.6 kN compared to 10.8 kN for SA2. These loads were observed at joint opening of 3.5 mm to 4 mm which is similar to that occurs in actual pavements due to temperature and moisture variations. After reaching the maximum pull-out load, the reduction in pull-out load per dowel with joint opening was greater for specimen SA2 than for specimens SV2N2 (as can be seen in Fig.9). In the case of aligned dowel bars, the pull-out force is primarily affected by frictional stress after complete breaking of bond, whereas bearing stress is also significant for misaligned dowels. Comparison of the results with GFRP dowels as shown in Fig. 5, reveals that the effect of vertical misalignment is significant for steel dowels primarily due to higher frictional forces. Also the bearing stress for misaligned dowels is more concentrated due to smaller diameter and high transverse stiffness compared to the GFRP dowels.

Although there is no clear consensus among the highway agencies about the allowable pull-out load in dowel bars in JPCP, the test loads for SA2 and SV2N2 exceeded the allowable load stated by some agencies such as Michigan Department of Transportation (MDOT) [35]. They state that the allowable pull-out stress per dowel bar should be about 0.4 MPa, i.e. for the 25 mm diameter and 38 mm dowel bars and embedded length of 227.5 mm the allowable pull-out loads are about 7 kN and 11 kN respectively. However their recommendation does not consider difference in mechanical property of the dowel material. Noting that limitation, the GFRP dowels (GA2 and GV2N2) in the current experiments showed lower pull-out loads than the above limits.

Fig.8 presents a comparison of the results of specimens with non-uniform vertical misalignment (SV2N2 and GV2N2) for both steel and GFRP dowels, and for non-uniform horizontal misalignment for specimens of GFRP dowels (GH2N4). The results also show that for same type and magnitude of dowel misalignment (SV2N2 and GV2N2) the steel dowels start to debond at a lower load but need a significantly higher force to completely debond and slip. The initial debonding of the dowel bars is affected significantly by the dowel bar diameter as mentioned before, whereas the slipping of the dowels is governed by the frictional force between the dowel bar and the concrete pavement, and the surface texture of the dowel. Since, the dowel-concrete interface friction encountered by epoxy-coated steel dowels is much higher than the GFRP[36], any increase in contact pressure due to bearing stress on the dowel bar produces a noticeable increase in the load required to open the joint. The maximum pull-out load for specimenSV2N2 can be observed at an approximately 4 mm joint opening. The load reached 14.6 kN(twice the allowable limit stated before) then decreased to a plateau value of 12.5 kN. For the specimens with GFRP dowels a maximum load of 8.85 kN was obtained after the start of slipping, then it linearly decreased to its final value of 7.5 kN at a 12 mm joint opening. For specimens with horizontal misalignment (GH2N4), significantly higher load was needed to open the joint. Similar to the vertically misaligned dowels, bearing pressure induced frictional force increases for horizontally misaligned dowels too. Unlike the vertical misalignment cases, no lifting of the specimens was expected to occur during the pull-out process (indicated by an FE analysis [26]). Large pull-out load was required for GH2N4 possibly due to the above reasons, and also the magnitude of misalignment was the highest one considered in this study. Cracks were observed at the concrete surface when the joint opening exceeded 6 mm and the concrete slab completely failed when the joint opening exceeded 9 mm.

In order to show the variation of the pull-out load with the joint opening, the comparison between steel and GFRP was made at joint opening of 3 mm, 6 mm and 12 mm as shown in Fig.9. Although

the GFRP dowels had bigger diameter compared to the steel dowels, the bar chart illustrates that GFRP dowels show significantly lower pull-out load. For similar diameter, the GFRP dowels could produce more reduction in pull-out load compared with steel dowels as many previous studies showed that the pull-out load increases with dowel bar diameter [34, 36]. Even for joint opening of 3 mm, the steel dowels exhibit higher pull-out load than the allowable limit stated by Michigan Department of Transportation (MDOT)[35].

Three misaligned dowel bars

Fig.10 presents the results of the slab specimens with three GFRP dowels:GA3, GV3P2, and GH3N2.As stated in Table 1, the specimen GA3 contains three aligned dowels; in specimen GV3P2 the central dowel is vertically misaligned while the outer ones are aligned; and finally in specimen GH3N2 the outer two dowels are non-uniformly (oppositely) misaligned and the central one is aligned. The results show that the initial debond of GA3 occurred at slightly higher load than the other specimens, however, at the post-initial stage the pull-out load is nearly flat with a small decrease until the joint is fully opened. The behaviour is similar to GA2 and GV2N2 (Fig. 5). While for specimens GV3P2, the vertical tilt of the middle dowel bar caused increased contact pressure due to bearing stress which initiated the debonding process at about 6 kN load over a small length at the stress concentration location and continued to progress towards complete debonding at 5 mm joint opening. After breaking of the bond, the behaviour becomes similar to that of GA3 because the pull-out load at that stage is only the load required to overcome sliding friction. For the specimen GH3N2, it can be noticed from the same figure that the load required to open the joint increases with higher joint opening. Also, the load magnitude (at joint opening of 6 mm and onward) is the highest among the specimens with three GFRP dowels of different orientations. This is because no slab-base separation occurs for horizontal misalignment; hence there is no possibility in the reduction of contact pressure between the slab and the dowels.

Relative deflection (RD) and dowel looseness due to slab movement

In order to investigate dowel looseness due to slab movement (expansion or contraction) and its effect on LTE, the deflections of the specimens were measured under vertical static load before, and after this movement. These tests were conducted to show the effect of slab movement on the specimens which had epoxy-coated steel dowel bars as compared with those specimens that had GFRP dowels, in order to investigate the suitability of using GFRP dowels to reduce joint lockup, RD and improve the LTE.

Fig.11 presents the results of the comparison between the RD for each specimen before, and after the slab movement. It can be observed that for all the specimens, RD after the movement is higher than its value before the movement. The increase in RD for the specimens with misaligned dowels – both steel and GFRP dowels is higher than that of the specimens of aligned dowels. The specimens of GFRP dowels exhibited a smaller increase in RD after the slab movement compared with those of the epoxy-coated steel dowels. This is possibly due to smooth surface texture of the GFRP dowels creates lower frictional forces, which leads to lower stresses at the dowel-concrete interface. The dowel bar socket may deteriorate less as a result of this.

In addition to RD (Relative Deflection), LTE (Load Transfer Efficiency) was also used to compare the performance of the steel and GFRP dowels. LTE is a criterion recommended in the AASTHO (1993) guide to evaluate the load transfer by dowel bars across a pavement joint. When a load is applied at the joint-face of a slab, both slabs are expected to deflect as a result of that. For an ideal load transfer across the joint, both loaded and unloaded slabs should exhibit same joint-face deflection. The LTE is measured as a ratio of the deflection of the unloaded side (d_u) to the deflection of the loaded side of the joint (d_l) as shown in Eq.2

$$LTE = \frac{d_u}{d_l} \times 100 \% \quad (2)$$

Fig.12 shows a comparison of the LTE before, and after, the pulling out and pushing back of the slabs. Since LTE was calculated as a function of joint-face deflections, a similar trend of results to those in Fig.11 was obtained. The reduction in LTE is smaller for specimens with aligned dowels than for those with misaligned dowels. Also, the specimens with GFRP dowels exhibited a smaller reduction in LTE compared with that of steel dowels. Even that the tested slabs are smaller than the typical slabs which may give higher LTE than that of typical slabs, the LTE can produce an indication for the change in LTE with dowels type and dowels misalignment for same size of slabs.

Results of the cyclic load test

The vertical deflection of the slabs was recorded under a static load of 40 kN after each set of 250,000 load cycles and the LTE was calculated from those readings. The results presented in Fig.13 show that the 38 mm GFRP dowels produce a lower RD (relative deflection) compared with 25 mm epoxy-coated steel dowel bars. The RD values for specimen GV2N2 show an increasing trend with number of load cycles, however, they remain lower than the SV2N2 values.

Fig.14 illustrates LTE (Load Transfer Efficiency) values for various specimens subjected to the cyclic load test. The results show a good LTE can be achieved by GFRP dowels during cyclic loading, principally due to the higher diameter of GFRP dowels being used. Similar to RD in Fig. 13, LTE for the GFRP specimen GV2N2 decreased at a higher rate with increasing number of load cycles compared to the steel specimens SV2N2. However, the LTE values still remained very high and within a range of 70-100% which is adequate for the load transfer across a typical joint [30]. The short slab length (less than the typical slabs) and un- deteriorate and un-compacted base may be the reasons of not clear monotonically decrease in LTE and remain it value more than 90%.

Fig.15 shows comparison between the dowel looseness due to slab movement and that due to the application of one million cycles of 40 kN load. The dowel looseness was calculated from the

growth in RD of the joint face (i.e. dowel looseness equals to RD after the slab movement minus RD before the slab movement). The results reveal that the looseness due to slab movement is higher for the steel dowels than for GFRP dowels, and for misaligned dowels than for aligned dowels cases. Pulling out and pushing back the slabs during the test (as a representation of the expansion and contraction of the concrete pavement) produced looseness for the epoxy-coated steel dowels higher than that due to one million load cycles; whereas, for the GFRP dowels, the looseness magnitude due to the slab movement is smaller than that due to the cyclic load effect. These performances are associated with the surface texture of both types of these dowels. The higher frictional stress between the steel dowels and the concrete causes more deterioration and looseness than that for GFRP dowels. The specimen GV2N2 shows slightly greater looseness than that of SV2N2 after one million cycles of 40 kN load. The movement of slabs with misaligned dowels created looseness at the joint face which consequently increases the unsupported length of the dowel bar segment at the joint. This increase in unsupported length is more of a concern for GFRP dowels than steel dowels because of GFRP dowels being weaker in the transverse direction. In spite of this looseness, the GFRP dowel showed very high LTE (see Fig.14).

SUMMARY AND CONCLUSIONS

An experimental study has been conducted to investigate dowel misalignment and joint lockup using epoxy-coated steel and GFRP dowels supported on a base-system with equivalent stiffness of a real pavement system. The study considered the effects of the position of the dowel bar during concrete casting; and evaluated the combined effect of dowel misalignment and cyclic traffic wheel load on LTE, relative deflection and dowel looseness for epoxy-coated steel and GFRP dowels. The GFRP dowels, as an alternative to epoxy-coated steel dowel bars, show a significant reduction in the load required for joint opening especially for excessive joint opening. The lower pull-out load reduces the stress at the dowel-concrete interface, dowel looseness and the mid-span stress in the

slab. Although only one cycle of push-out and push-back was conducted, the results illustrate that the axial movement of the slab produces a significant increase in dowel looseness and a decrease in LTE compared with the effect due to repeated traffic load especially when dowel misalignment exists. The use of GFRP dowels may improve the pavement performance by reducing the joint lockup and enhancing the LTE. Since the expansion and contraction of pavements are continuous during the service life of a road, more deterioration may occur in the concrete surrounding steel dowels as compared to GFRP dowels. This deterioration increases rapidly when dowel misalignment exists and may cause failure similar to the one witnessed in specimen GH2N4. It should be mentioned that although the experiments were designed after careful considerations of various parameters, the current set of results is by no means comprehensive and does not include other effects like curling of slabs due to temperature changes. This will be addressed in a subsequent study. The experimental results even though clearly indicate better performance of GFRP dowels under the test conditions, more experimental data are necessary for detailed quantitative evaluation. Despite the above limitations, it was reassuring to note that the general trend of the tested specimens is consistent with the results in literature.

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COMPETING INTERESTS STATEMENT

The authors declare no competing interests.

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(a)

(b)

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Table 1. Test matrix for the experimental specimens

Slab Dimensions (mm)	Number, diameter and material of dowel	Code of specimens	Misalignment type	Magnitude of misalignment per half length of dowel (mm)
2 slabs each one (450 × 900 × 200)	2 ϕ 38 mm GFRP	GA2	Aligned	0
		GH2N4	Horizontal	25
		GV2N2	Vertical	12.5
2 slabs each on (450 × 1200 × 200)	3 ϕ 38 mm GFRP	GA3	Aligned	0
		GH3N2	Horizontal	12.5
		GV3P2	Vertical	12.5
2 slabs each one (450 × 900 × 200)	2 ϕ 25 mm steel	SA2	Aligned	0
		SV2N2	Vertical	12.5