

Evaluation of Structural Test Results for the O-Dowel™

by

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Introduction

In May 2017, O-Dowel, Inc. provided epoxy-coated, galvanized hollow steel highway dowels, branded as O-Dowel™, to Dr. Julie Vandebossche of the University of Pittsburgh Department of Civil and Environmental Engineering for testing with repeated simulated heavy vehicle loads in a typical concrete slab installation. Approximately 10 million load cycles had been applied when the test was terminated in July of 2017.

The University of Pittsburgh allows their researchers only to perform testing and does not allow them to engage in direct product evaluations. The evaluation provided in this paper is based on the test results provided by the University of Pittsburgh (Vandebossche 2017), but is the sole work, opinion and responsibility of the author. This report should not be construed to reflect the views of the University of Pittsburgh and does not constitute an endorsement of the O-Dowel™ product by the University of Pittsburgh.

Test Description

The tubular dowels provided for testing measured approximately 1.625 inches in diameter x 18 inches in length. Three of the dowels were installed in precisely drilled holes on 12-inch centers in a 0.25-in thick piece of plywood joint form, and were supported on steel frame chairs on either end. The dowels were tied to the chairs to ensure proper alignment during slab fabrication. The bars were installed in the slab with the outside bar located 6 inches from the edge of a 7.5-in thick slab measuring 6 ft wide and 10 ft in length with a transverse joint located 5 ft from either end of the slab. The joint was formed using a ¼-in thick piece of plywood (previously described) to ensure that all load transferred across the joint was carried by the dowels (i.e., without contribution of aggregate interlock). Figures 1 and 2 show the general layout of the dowels and the test slab. The test arrangement represents 1/6-panels of two adjacent 12-ft wide by 15-ft long jointed plain concrete pavement slabs (and the included transverse joint). The slab was cast and then cured with wet burlap for 28 days.

The slab support system comprises a rigid steel beam frame that has been filled with concrete and covered with a double-layer of engineered vibration isolation pad material that is believed to simulate a foundation stiffness (k-value / modulus of subgrade reaction) of approximately 200 psi/inch. This pad material is covered with plastic before the test specimen is cast on it.

The test slab was loaded using two hydraulic actuators operating on 12-in diameter load plates placed adjacent to the outer edge of the slab and centered 7 inches on either side of the transverse joint (i.e., directly over the outside dowel), as shown in figures 3 and 4. The actuator load profiles are shown in figure 5 and consist of haversine waveforms that range (nominally) from 500 to 9500 lbs and are 90 degrees out of phase with each other. The duration of the complete load cycle is 0.2 seconds and corresponds to a simulated vehicle speed of about 45 mph.

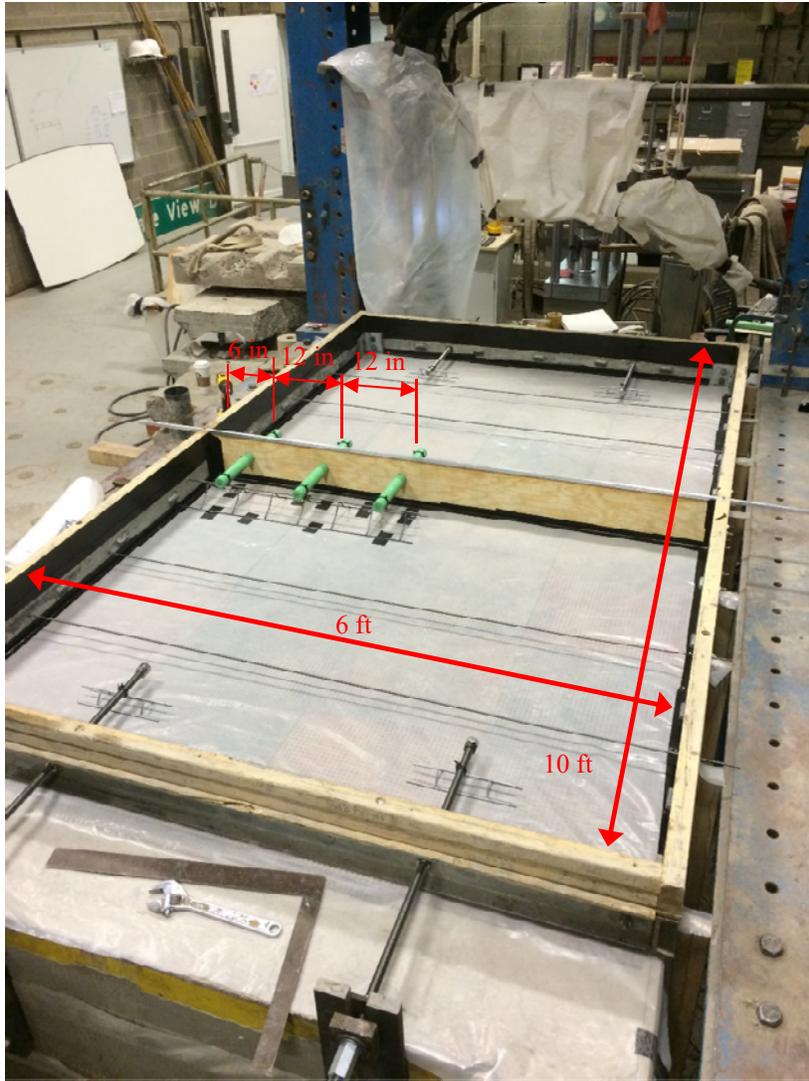


Figure 1. Test slab dimensions and O-Dowel™ locations in test specimen form prior to placement of concrete (Vandenbossche, 2017).

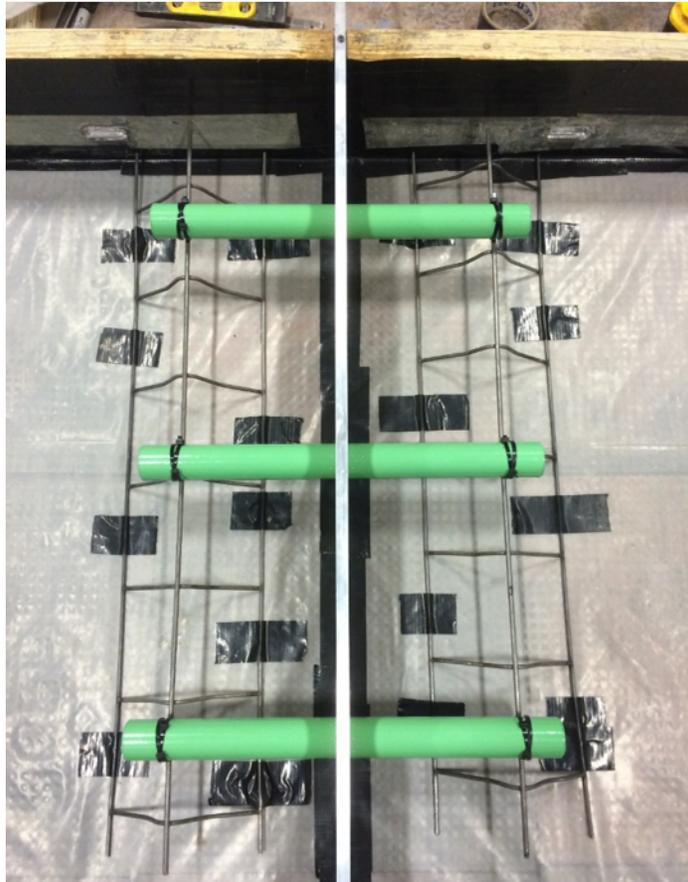


Figure 2. Close-up photo of O-Dowel installation prior to testing (Vandenbossche, 2017).



Figure 3. Photo of load plate and LVDT placement for the University of Pittsburgh dowel/slab test program (Vandenbossche, 2017).

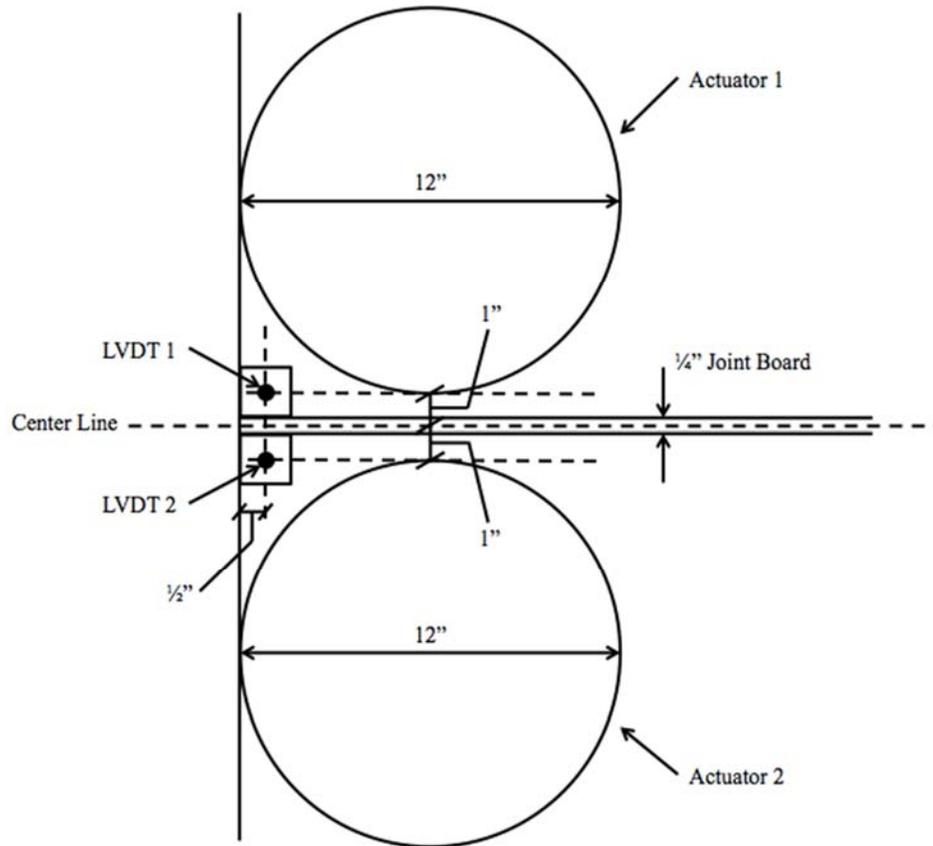


Figure 4. Plan view schematic of load plate and LVDT placements.

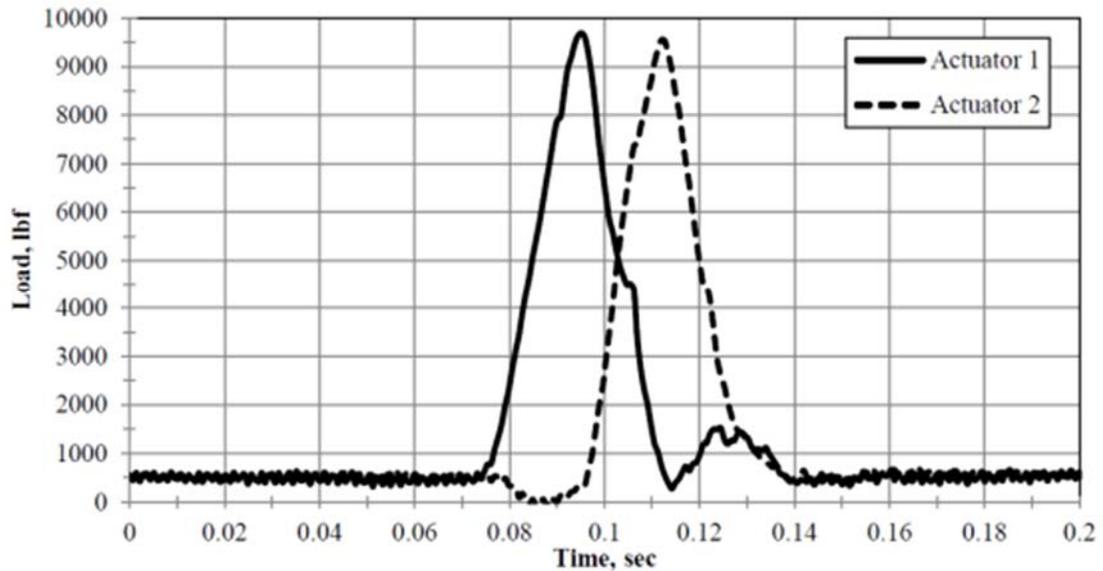


Figure 5. Actuator loading profiles (Vandenbossche, 2017).

Linear variable differential transformers (LVDTs) were mounted one inch on each side of the transverse joint and $\frac{1}{2}$ inch from the edge of the slab, as shown in figures 3 and 4. The LVDTs

were used to measure vertical movements of each side of the joint; the measures obtained were used to compute load transfer efficiency and differential deflection under load. Measurements were obtained “on the fly” (i.e., dynamically, while the system was running) as well as using static loads by interrupting the load program momentarily.

Presentation and Evaluation of Test Results

Discussion of the Test Protocol and its Implications

Before considering the data obtained from the University of Pittsburgh tests of the O-Dowels™, it is important to provide a proper frame of reference for the test results.

Most dowelled joints in in-service pavements contain one dowel per foot of joint (typically 11-12 per travel lane-joint), and aggregate interlock (below the saw cut for the joint) does influence the measured slab deflections and computed joint load transfer efficiency (with the magnitude of contribution depending upon slab temperature and restraint, slab geometry, concrete aggregate gradation and properties, etc.). In addition, dowels in in-service pavements are subjected to traffic loads of varying magnitudes and with significant vehicle wander such that only a relatively small proportion of vehicle loads are at the full legal load and are applied directly over the critical dowel (generally the one closest to the edge of the pavement).

The testing performed using the University of Pittsburgh’s accelerated load test facility (ALF) can be considered to be a much more rigorous test of dowel structural performance on a load-by-load basis for several reasons:

1. Only three dowels are installed in a half-joint width (compared to 5-6 typically found in the field), so the load carried by each dowel is somewhat higher than would be observed in the field.
2. The use of the ¼-in plywood joint form results in absolutely no aggregate interlock across the transverse joint, ensuring that the dowels carry essentially *all* of the load that is transferred across the joint. This further increases the load carried by each dowel over what would be observed in new pavement in the field, and probably results in higher dowel deflections.
3. The plywood joint form also produces a ¼” joint width over the full depth of the joint. Sawed joints for 15-ft panels typically have very little width below the saw cut except during cold weather and after long-term shrinkage has taken place. The wider joint used in the Pittsburgh test likely results in higher differential deflection measurements across the joint than would be observed in the field shortly after construction.
4. Since the actuators are positioned directly over the dowel closest to the slab edge, *every applied load produces maximum bearing stress under the critical dowel*. Since traffic loads vary in both magnitude and position for in-service loads, *each Pittsburgh ALF load can be considered to represent the accumulated effects of several typical load applications in the field*.
5. The placement of the LVDTs near the slab corners almost certainly results in higher deflection measurements that would be obtained in the field using a falling weight deflectometer (FWD), where deflection measurements are typically obtained directly beneath the applied load (6 inches or more from the panel edges) and from the first sensor, typically 12 inches away on the other side of the joint.

6. The Pittsburgh ALF test slabs are only 7.5 inches thick and represent two 1/6-panels of typical full-sized slabs. In-service pavements containing 1.5-in (or larger) diameter dowels would probably be much thicker (10 inches or more) and, as a result, much stiffer. These thicker, stiffer slabs would distribute applied loads over a larger area and would transfer less of the load across the joint through the critical dowels. In addition, thicker slabs are stiffer and exhibit smaller overall deflections than thinner slabs when other factors are held constant (which impacts load transfer efficiency calculations for any given differential deflection).
7. The 1/6-panels that comprise the test specimen are vertically unrestrained on all sides (except for the doweled joint, of course) and can be expected to experience higher deflections and movements than would be observed in the field with full-sized slabs – particularly those that are tied and/or doweled together.
8. Most highway agencies perform falling weight deflectometer (FWD) tests (an impulse load) on in-service pavements to determine the load transfer efficiency of their doweled joints. The Pittsburgh ALF applies a load that is a repeated dynamic (haversine wave form) load, which has the potential to induce some behavioral resonance in the slab. This resonance would serve to artificially increase measured slab deflections and might increase dowel bearing stresses accordingly.

In all of these regards, the Pittsburgh ALF test is much more severe (on a load-by-load basis) than field conditions and it is *highly likely that the test results cannot be compared directly with field measurements* for comparable numbers of equivalent 18-kip single axle loads (ESALs). It is reasonable to assume that *the observed load transfer and differential deflection histories are greatly accelerated compared to what would be observed in the field* for these dowels after the completion of any given number of load cycles.

Test Results and Discussion – Load Transfer Efficiency

With this context in mind, consider figures 6 through 9, which present load transfer efficiency (LTE) histories for the test specimen containing the three O-Dowels™ for static and dynamic load conditions, with either the approach or leave sides of the joint being loaded. In this study, LTE was computed as:

$$LTE = 100 \frac{d_u}{d_l}$$

where:

LTE	=	joint load transfer efficiency
d_u	=	deflection of the corner of the unloaded slab at the LVDT
d_l	=	deflection of the corner of the loaded slab at the LVDT

Figure 6 contains a plot of load transfer efficiency (LTE) versus cumulative loading cycles for static loading conditions (similar to the type of loading imparted during a Benkelman beam test) for placement of the load on the approach (upstream) side of the transverse joint. For comparison purposes, it also presents data obtained from identical testing of standard 1.5-inch diameter, 18-inch long solid epoxy-coated steel conventional dowels (performed in early 2017). Figure 7 presents a similar plot for static loading on the leave (downstream) side of the joint. Figures 8 and 9 present the data obtained for dynamic loading of the approach and leave sides of the joint, respectively. Dynamic loading conditions are considered similar to the loadings imparted by moving vehicle loads and by falling weight deflectometer (FWD) testing.

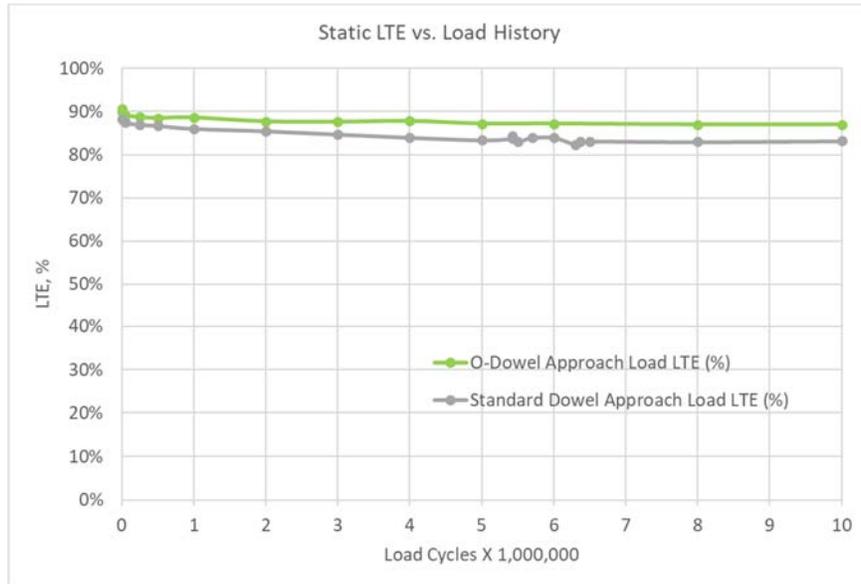


Figure 6. Comparison of static LTE vs. load cycles for O-Dowel and conventional 1.5-in diameter solid epoxy-coated steel dowel – approach side loading.

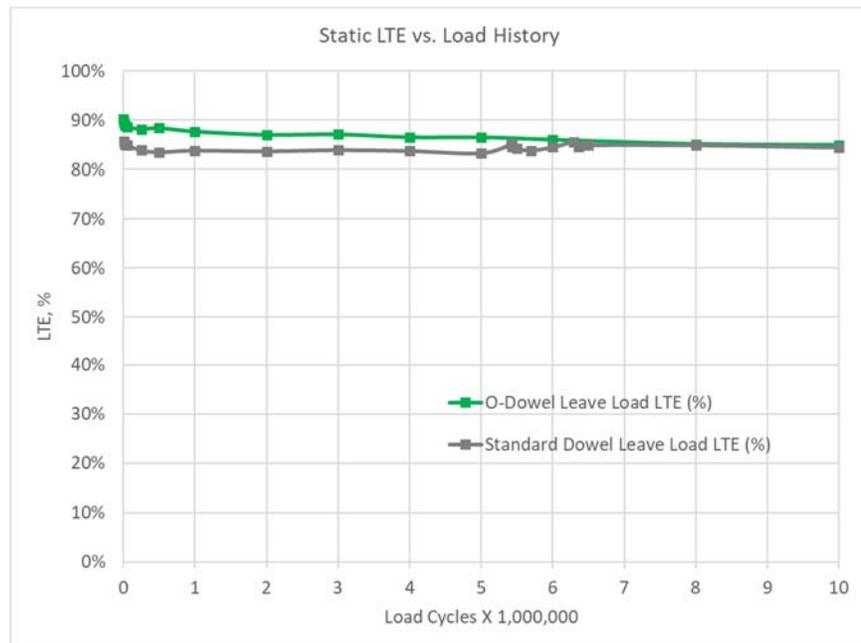


Figure 7. Comparison of static LTE vs. load cycles for O-Dowel and conventional 1.5-in diameter solid epoxy-coated steel dowel – leave side loading.

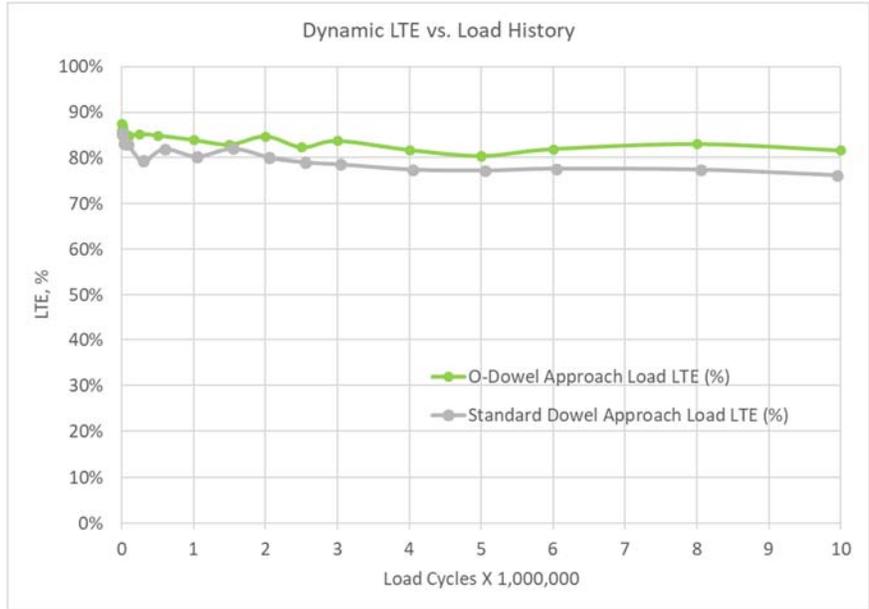


Figure 8. Comparison of dynamic LTE vs. load cycles for O-Dowel and conventional 1.5-in diameter solid epoxy-coated steel dowel – approach side loading.

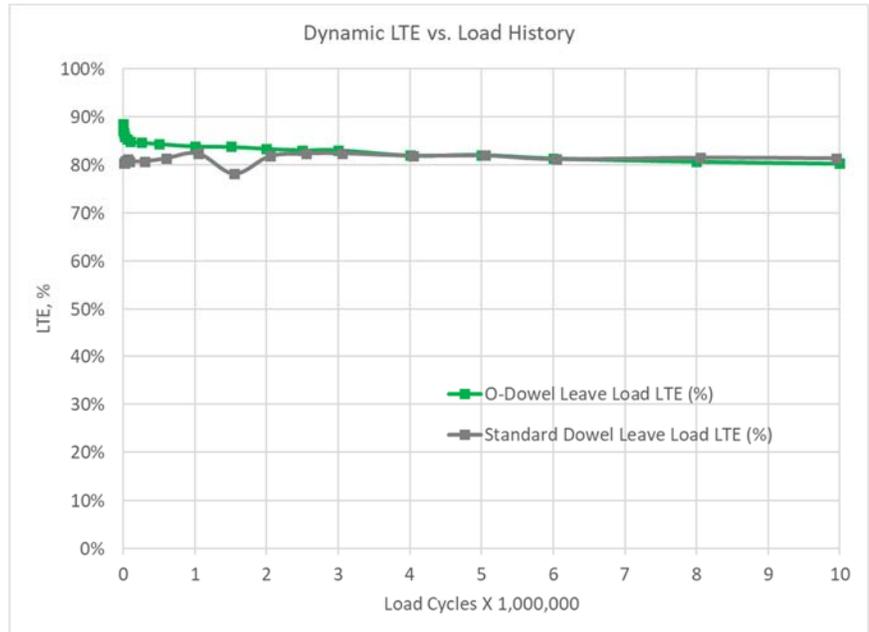


Figure 9. Comparison of dynamic LTE vs. load cycles for O-Dowel and conventional 1.5-in diameter solid epoxy-coated steel dowel – leave side loading.

The data presented in figures 6 – 9 indicate that the O-Dowel configuration tested in this program has very good LTE characteristics, with static LTE values starting above 90 percent and decreasing by less than 6 percent over 10 million load cycles, and dynamic LTE values starting around 88 percent and remaining above 80 percent throughout the test. LTE failure criteria typically used by highway agencies range from 50 to 70 percent, so the test values greatly exceed those criteria.

It is worth noting that the O-Dowel LTE values were comparable to or better than those of 1.5-in solid epoxy-coated steel dowels in all four load configurations (i.e., static or dynamic with load placement on either the approach or leave side of the joint).

The leave side-loaded LTE values are generally slightly lower than the approach side-loaded under both static and dynamic loading. Assuming that dowel support, concrete stiffness, foundation stiffness, etc. are uniform throughout the slabs, one would expect the LTE values to be identical for loading on either side of the joint. There are several possible explanations for the consistent differences observed in the approach side-loaded and leave side-loaded LTE values, including the possibility of some slight difference in dowel support or foundation stiffness across the formed joint or that the differences are an artifact of some aspect of the test stand construction or test protocol. This is discussed further in the next section.

The LTE values for dynamic loading are generally lower than the corresponding static load LTE values at any given load cycle count interval. This is to be expected because slab deflections are generally lower under dynamic loads than static loads, but the differential deflection across the joint remains more constant; therefore, the difference in deflection across the joint is a greater percentage of the lower overall deflection for dynamic loads, resulting in lower LTE values. This illustrates why LTE is an imperfect indicator of dowel and joint behavior because it is based on total system deflection, which is impacted by rate of loading, foundation stiffness, slab stiffness and other factors that have nothing to do with the dowel. A more pure measure of dowel effectiveness is relative (or differential) deflection, which is discussed below.

Test Results and Discussion – Relative Deflection

Relative deflection (RD or d-rel), also sometimes called differential deflection (DD), is computed as the absolute difference in deflection between the loaded and unloaded sides of a joint. RD is considered by some pavement engineers to be a better indicator of joint system function than load transfer efficiency because it is primarily a function of joint width and dowel/aggregate interlock properties while LTE is dependent upon these factors as well as slab thickness, foundation stiffness, and other parameters not related to the joint.

As an example, consider a joint system where the deflections of the loaded and unloaded sides of the joint are 2 mils and 1 mil, respectively. The computed d-rel is 1 mil (a very low number indicating high joint function), but the LTE is 50 percent (which is less than most failure criteria of 50 - 70 percent and would be considered unacceptable). If the foundation stiffness is decreased but the joint parameters remain constant, we might see the deflection values increase to 5 mils and 4 mils, still resulting in a d-rel of 1 mil (correctly indicating the function of the joint) but with the LTE increasing to 80 percent (a favorable number that, in this case, more accurately characterizes the joint function). Examples can also be cited where LTE values increase to the point of acceptability as total deflection increases, even when d-rel values indicate that joint function is poor. The bottom line is that d-rel is a better indicator of joint function than LTE.

Figures 10 through 13 present relative deflection histories for the test specimen containing the three O-Dowels™ for static and dynamic load conditions with either the approach or leave sides of the joint being loaded. Figure 10 contains a plot of relative deflection (d-rel) versus cumulative loading cycles for static loading conditions (similar to the type of loading imparted during a Benkelman beam test) for placement of the load on the approach (upstream) side of the

transverse joint. For comparison purposes, it also presents data obtained from identical testing of standard 1.5-inch diameter, 18-inch long solid epoxy-coated steel conventional dowels (performed in early 2017). Figure 11 presents a similar plot for static loading on the leave (downstream) side of the joint. Figures 12 and 13 present the data obtained for dynamic loading of the approach and leave sides of the joint, respectively. Dynamic loading conditions are similar to those imparted by moving vehicle loads and by falling weight deflectometer (FWD) testing.

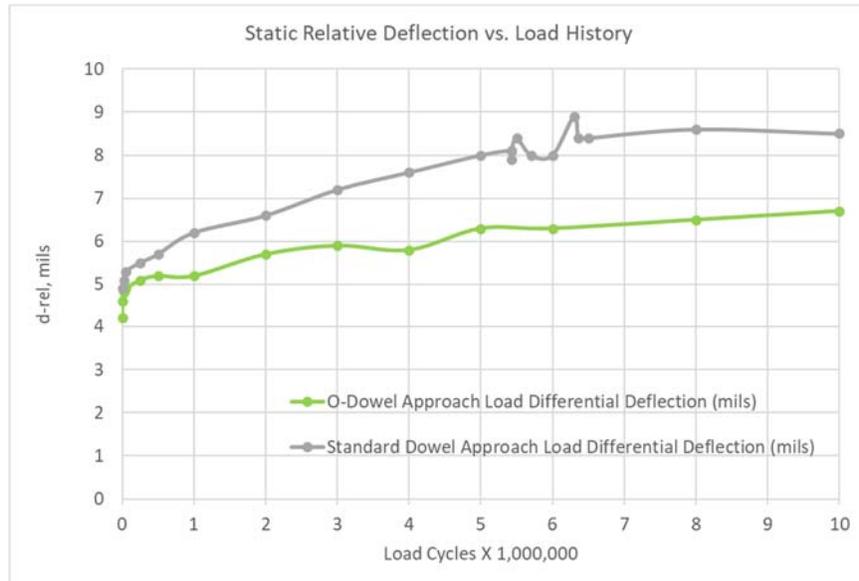


Figure 10. Comparison of static load relative deflection vs. load cycles for O-Dowel and conventional 1.5-in diameter solid epoxy-coated steel dowel – approach side loading.

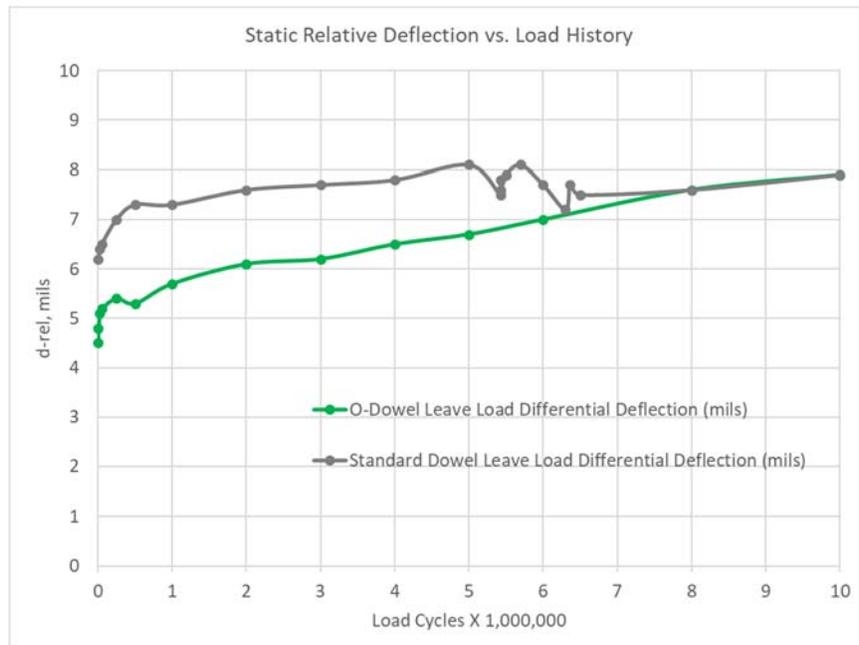


Figure 11. Comparison of static load relative deflection vs. load cycles for O-Dowel and conventional 1.5-in diameter solid epoxy-coated steel dowel – leave side loading.

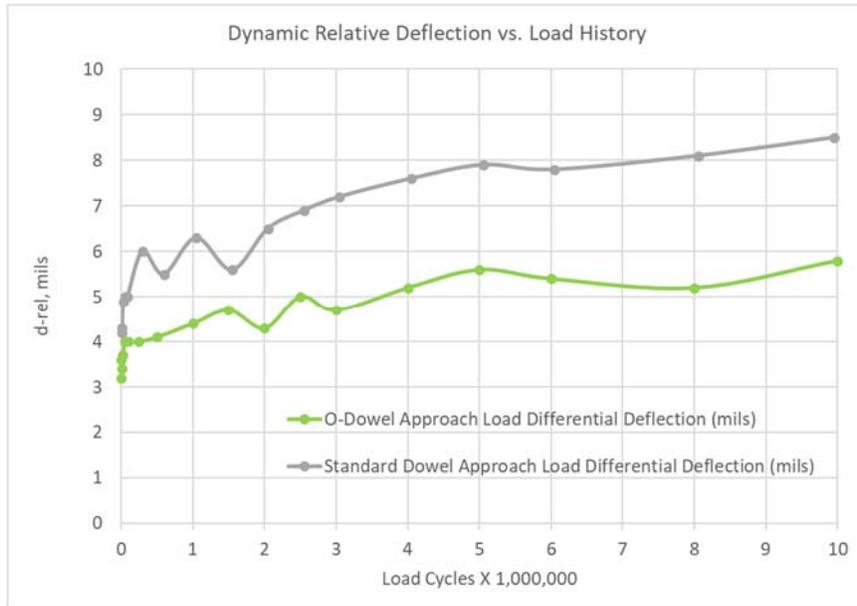


Figure 12. Comparison of dynamic load relative deflection vs. load cycles for O-Dowel and conventional 1.5-in diameter solid epoxy-coated steel dowel – approach side loading.

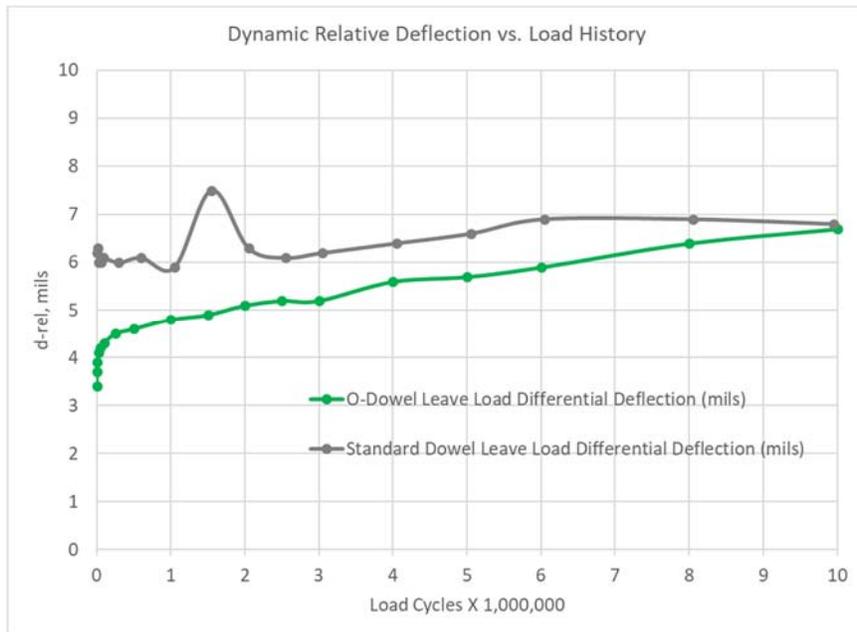


Figure 13. Comparison of dynamic load relative deflection vs. load cycles for O-Dowel and conventional 1.5-in diameter solid epoxy-coated steel dowel – leave side loading.

The O-Dowel d-rel values associated with static loading (shown in figures 10 and 11) started at around 4 mils and increased to about 7 or 8 mils (for the approach and leave side loading conditions, respectively). The O-Dowel d-rel values associated with dynamic loading, similar to what would be observed with Falling Weight Deflectometer testing, started at around 3 mils and increased to about 6 or 7 mils (for the approach and leave side loading conditions, respectively), as shown in figures 12 and 13. In all figures, the O-Dowel d-rel values are typically 1 – 3 mils lower than those observed with conventional solid epoxy-coated steel dowels.

It is not clear that any highway agencies currently have limiting criteria (e.g., maximum allowable values) for differential deflection measurements. American Concrete Institute Committee 360 limits “joint stability” (the ACI term for differential deflection) for slabs-on-ground (i.e., industrial flooring) applications to 10 mils for hard-wheeled lift trucks and 20 mils for lift trucks with larger cushioned rubber wheels, but ACI provides no guidance on acceptable joint stability or differential deflection values for highway pavements. Therefore, it is difficult to evaluate the results of this test in terms of any definitive criterion. However, the differential deflection values observed in these tests would easily meet either of the ACI limits for industrial floors.

It can be observed in figures 10 through 13 that the d-rel values for leave side loading are typically slightly higher than for approach side loading at any given cycle count. This is consistent with the slightly lower LTE values observed for leave side loading in figures 6 through 9. There are a few possible explanations for these differences, as described previously and not repeated here.

General Discussion of LTE and Deflection Test Data

The LTE and DD results obtained in Pittsburgh test program are quite conservative because field conditions for new construction will include load transfer that is provided by both dowels and aggregate interlock, while the Pittsburgh test was conducted without any aggregate interlock contribution. The added contribution of aggregate interlock under service conditions would certainly increase LTE and decrease differential deflection values from what was observed in this test program.

Therefore, while the results of the Pittsburgh load testing described here cannot be compared directly with field performance measures and criteria, they indicate that the O-Dowel™ system that was evaluated meets generally accepted load transfer efficiency requirements for up to 10 million critical load cycles, and will probably meet the criteria for many more load cycles in new construction applications where aggregate interlock is also present.

The following observation was made at the conclusion of a multi-year study evaluating the performance of several alternative dowel installations at locations throughout the U.S.:

“Doweled joints with LTEs 85 percent or less and/or a differential deflection of greater than 0.13 mm (5 mils) (with the load on each side of the joint) in 5 years or less are unlikely to provide satisfactory long term performance.” (Larson and Smith, 2005)

The LTE and differential deflection results obtained in this test program meet the criteria described above, with dynamic LTE values hovering around 90 percent and DD values of 3 – 5 mils throughout the program. In addition, it must be recalled that the results of the Pittsburgh test program are quite conservative because Larson and Smith were evaluating the performance of dowels in in-service pavements for which load transfer is provided by both dowels and aggregate interlock, while this test was conducted without any aggregate interlock contribution. The added contribution of aggregate interlock under service conditions would certainly increase LTE and decrease differential deflection values from what was observed in this test program.

In summary, while the results of the load testing being evaluated here cannot be compared directly with field performance measures and criteria, they still meet and exceed the criteria that

have been suggested for consideration even though the test conditions are considered to be more severe than field conditions.

Test Results and Discussion – Dowel Diameter Measurements

Dowel diameters were measured at several locations, both before and after the load testing, to determine whether any permanent deformation developed in the dowels as a result of the repeated load applications. Significant compression or wear across the vertical diameter of the dowels could contribute to a loss of load transfer efficiency over time.

Five diameters of each dowel were measured (such that the angle between successive diameter measurements was 36 degrees) at 5 locations for each dowel – at the joint and ¼ and ½ inch on either side of the joint. Measurement locations were scribed into the dowels before installation in the test slab so that the same measurement points could be used both before and after the load testing. The pre-test measurements were reportedly accomplished after simply wiping the dowels clean of any debris or dirt; conducting the post-test measurements required that the dowels be carefully retrieved from the slab, wiped clean, and visually inspected for damage prior to measurement.

Table 1 contains the measured dowel diameters from before and after testing for each of the three dowels (where dowel 1 was located closest to the slab edge and dowel 3 was the most interior dowel). These data show that the dowel diameter remained approximately constant (measurement difference less than 0.005 inches in most cases and less than 0.01 inches in all cases). Slight increases in dowel diameter (indicated in bold font in Table 1) are believed to be due to the embedment of concrete dust on the dowel surface and random variations in measurement accuracy.

Table 1. O-Dowel™ Diameters (inches) Before and After Testing (Vandenbossche 2017).

Dowel	Angle	Before Actuator Testing					After Actuator Testing				
		Location Relative to Center of Bar, in					Location Relative to Center of Bar, in				
		-0.5	-0.25	0	+0.25	+0.5	-0.5	-0.25	0	+0.25	+0.5
1	0	1.6440	1.6430	1.6435	1.6435	1.6445	1.6430	1.6415	1.6470	1.6430	1.6420
	36	1.6435	1.6425	1.6425	1.6420	1.6400	1.6405	1.6405	1.6425	1.6410	1.6405
	72	1.6410	1.6420	1.6410	1.6415	1.6425	1.6390	1.6390	1.6485	1.6370	1.6380
	108	1.6415	1.6415	1.6415	1.6415	1.6415	1.6410	1.6420	1.6470	1.6400	1.6410
	144	1.6415	1.6415	1.6415	1.6415	1.6410	1.6410	1.6420	1.6440	1.6395	1.6400
2	0	1.6490	1.6490	1.6500	1.6470	1.6470	1.6515	1.6470	1.6525	1.6480	1.6525
	36	1.6480	1.6450	1.6445	1.6445	1.6450	1.6420	1.6435	1.6440	1.6420	1.6420
	72	1.6445	1.6440	1.6435	1.6425	1.6430	1.6400	1.6415	1.6415	1.6415	1.6415
	108	1.6400	1.6400	1.6400	1.6405	1.6400	1.6430	1.6415	1.6480	1.6420	1.6425
	144	1.6405	1.6405	1.6410	1.6405	1.6400	1.6445	1.6450	1.6470	1.6445	1.6440
3	0	1.6485	1.6475	1.6490	1.6490	1.6490	1.6465	1.6465	1.6470	1.6445	1.6455
	36	1.6485	1.6490	1.6485	1.6490	1.6500	1.6495	1.6495	1.6490	1.6480	1.6470
	72	1.6405	1.6395	1.6400	1.6400	1.6400	1.6405	1.6395	1.6475	1.6405	1.6400
	108	1.6400	1.6400	1.6405	1.6400	1.6405	1.6425	1.6455	1.6510	1.6405	1.6425
	144	1.6415	1.6415	1.6420	1.6415	1.6415	1.6425	1.6420	1.6445	1.6435	1.6410

Note: Text in bold indicates diameter increasing.

A visual inspection of the bars after testing revealed no visible deformation in any of the dowels and no indications of significant wear or damage to the epoxy coatings of any of the dowels, as seen in figure 14.



Figure 14. Photo of O-Dowels after completion of test and extraction from test panel.

Conclusions

The results of the accelerated pavement testing performed on the O-Dowel™ product at the University of Pittsburgh indicate that these dowels are capable of providing structural performance in concrete pavements that is comparable to (or better than) that of conventional epoxy-coated solid steel dowels when properly designed (i.e., with proper size and spacing).

References

1. American Concrete Institute 2010. Guide to Design of Slabs-on-Ground. ACI 360R-10. American Concrete Institute. Farmington Hills, MI.
2. Vandebossche, J. M. 2017. August 8, 2017 letter report to Mr. Chris Schenk of O-Dowel, Inc. describing project test results. University of Pittsburgh Department of Civil and Environmental Engineering, Pittsburgh, PA.