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RESEARCH ARTICLE - ENGINEERING (MISCELLANEOUS)

Experimental Evaluation of Demountable Glass Fiber-Reinforced Polymer Dowel Bar System Incorporating Steel and Fiber-Reinforced Polymer Rings in Precast Concrete Pavements

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Abstract

This study presents an experimental evaluation of a demountable Glass Fiber-Reinforced Polymer (GFRP) dowel bar system incorporating steel and Fiber-Reinforced Polymer (FRP) rings for concrete pavement applications. The primary objective is to investigate the load-transfer behavior and structural performance of the proposed system and to compare its response with conventional steel ring configurations. An experimental program is conducted using concrete joint specimens subjected to monotonic vertical loading, where load–displacement behavior, load transfer capacity, and failure characteristics are evaluated. The experimental results indicate that specimens incorporating FRP rings can exhibit superior performance compared to those with steel rings. The maximum load capacity increases by approximately 30–35%, reaching peak values of about 60kN, while the corresponding vertical displacement is reduced by nearly 20–25% relative to reference specimens. Furthermore, the GFRP-based systems demonstrate improved post-peak behavior and more stable load–displacement responses, indicating enhanced load transfer efficiency and reduced stress concentration at the joint interface. Overall, the proposed demountable GFRP dowel bar system shows significant potential as a sustainable and efficient alternative to traditional steel dowel systems in concrete pavements, offering improved mechanical performance, corrosion resistance, and ease of disassembly and replacement.

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Keywords: Demountable Joints; Load Transfer Efficiency; Steel Sleeves; Slab Replacement; Stress Concentration; Structural Performance.

1. Introduction

Concrete pavements used in high-traffic highway networks require continuous maintenance and rehabilitation due to the stresses induced by repetitive traffic loading and environmental conditions. Pavements constructed using materials with limited durability may deteriorate within a relatively short period of service. Smith and Snyder [1], Tayabji et al. [2], and Priddy et al. [3] reported that conventional pavement systems may experience significant deterioration within five to ten years under heavy traffic conditions. Maintenance and rehabilitation operations often require long road closures to allow concrete to reach adequate strength before reopening to traffic. According to Olidis et al. [4], infrastructure maintenance activities and traffic interruptions represented major economic challenges for transportation agencies. Therefore, developing pavement systems that enable rapid construction and efficient maintenance has become an essential objective for modern transportation infrastructure. Precast concrete pavement (PCP) technology has emerged as an effective solution for accelerating pavement construction and rehabilitation. PCP systems allow pavement slabs to be fabricated off-site under controlled conditions and installed on-site after achieving the required strength. Previous studies conducted by Novak et al. [5] demonstrated that precast pavement systems provide improved quality control and reduced construction time. Similarly, Priddy et al. [6] reported that precast concrete panels can significantly reduce traffic disruption during pavement rehabilitation projects. Syed and Sonparote [7] further highlighted that PCP systems represent an efficient alternative for the rapid rehabilitation of heavily trafficked highway networks. Load transfer across transverse joints is a critical aspect affecting the structural performance of rigid pavements. For several decades, epoxy-coated steel dowel bars have been widely used to improve load transfer efficiency between adjacent concrete slabs. These dowel bars help distribute wheel loads across the joint, thereby reducing slab deflection and minimizing stress concentration within the concrete. However, conventional steel dowel systems may suffer from durability problems due to corrosion and repeated loading. Al-Humeidawi and Mandal [8] investigated the performance of GFRP dowels in jointed plain concrete pavements and demonstrated their potential to improve load transfer efficiency while reducing durability issues associated with steel dowels. Several analytical and numerical studies have been conducted to evaluate stress distribution in rigid pavements. El-Maaty et al. [9] investigated the influence of material parameters on the behavior of jointed rigid pavements using advanced analytical techniques. Similarly, Shoukry et al. [10] applied numerical simulations to identify critical stress concentrations around dowel bars and pavement joints. Earlier experimental studies conducted

Nomenclature &Symbols			
PCP	Precast Concrete Pavement	ASTM	American Society for Testing and Materials
FRP	Fiber-Reinforced Polymer	GFRP	Glass Fiber Reinforced Polymer
LVDT	Linear Variable Differential Transducer	LTE	Load Transfer Efficiency
UHPC	Ultra-High Performance Concrete	mm	Millimeter
kN	Kilo Newton	MPa	Mega Pascal
Δ	Displacement	fc	Compressive Strength of Concrete
AASHTO	The American Association of State Highway and Transportation Officials	DL1, DL2	Indices Used to Describe Dowel Looseness Under Cyclic Loading

by Teller and Cashell [11] examined the performance of doweled joints under repetitive loading and highlighted the importance of proper load transfer mechanisms for maintaining pavement integrity. Further investigations have focused on alternative dowel materials and their interaction with surrounding concrete. Murison [12] evaluated the performance of concrete-filled GFRP dowels in jointed concrete pavements, while Murison et al. [13] studied the structural behavior of GFRP dowels under static loading conditions. The American Association of State Highway and Transportation Officials (AASHTO) proposed the standard test method T253 for evaluating dowel bar performance in laboratory conditions [14]. Porter et al. [15] later modified this testing procedure to improve the reliability of the experimental measurements. Additional experimental investigations by Porter et al. [16] examined the structural behavior of glass fiber composite dowel bars and assessed their potential application in highway pavement systems. Porter and Pierson [17] also evaluated alternative dowel materials and confirmed the feasibility of using non-metallic dowels in concrete pavements. More recently, the fatigue performance of dowel bars has been investigated under repeated loading conditions. Yin et al. [18] examined the fatigue behavior of epoxy-coated steel dowels and reported that load transfer efficiency gradually decreases after several million load cycles due to dowel looseness. Numerical investigations conducted by Al-Humeidawi and Mandal [19] further demonstrated that GFRP dowels can maintain adequate load transfer efficiency while reducing stress concentration at the dowel-concrete interface. Experimental research on FRP-reinforced pavement systems has also shown promising results. Benmokrane et al. [20] evaluated full-scale jointed plain concrete pavement sections reinforced with GFRP dowels and reported satisfactory load transfer performance under both static and cyclic loading conditions. Vijay et al. [21] confirmed that GFRP dowels can provide structural performance comparable to conventional steel dowels when designed according to AASHTO specifications. In addition, Li et al. [22] investigated the contact stress between dowels and surrounding concrete and found that increasing the dowel diameter can significantly reduce local compressive stresses at the joint interface. Besides strength and stiffness, toughness represents an important mechanical property that reflects the ability of a material to absorb energy before failure. Mindess et al. [23] defined toughness as the resistance of a material to crack initiation and propagation. According to ASTM standards [24], toughness can be quantified by evaluating the area under the load-displacement or stress-strain curve. Li [25] further emphasized the importance of toughness in assessing the structural performance of composite materials used in civil engineering applications. Alternative load transfer systems have also been proposed to improve pavement durability and maintenance efficiency. Al-Jelawy and Kinaine [26] investigated the use of ultra-high-performance concrete (UHPC) link slabs as an alternative to conventional steel dowel bars in rigid pavements. Their experimental results showed that UHPC link slabs can increase load-carrying capacity and improve crack control. Subsequent research by Al-Jelawy et al. [27] ascertained that UHPC link slabs exhibit improved durability and reduced joint distress compared with conventional doweled joints. Numerical investigations conducted by Alzamily et al. [28] also demonstrated that UHPC-based systems provide enhanced fatigue resistance and improved load transfer performance. Recent experimental and field studies have further confirmed the effectiveness of FRP-based dowel systems in concrete pavements. Montaigu et al. [29] investigated the structural performance of GFRP dowels in jointed plain concrete pavements and reported improved cracking behavior and stable load transfer performance under static loading conditions. Parvini [30] conducted a field performance evaluation of concrete pavements reinforced with GFRP dowel bars under heavy traffic loading and observed that the GFRP dowel system maintained strong load transfer characteristics with minimal deterioration over time. In addition, Ziemann et al. [31] carried out an experimental comparison between FRP, epoxy-coated steel, and stainless-steel dowel bars and highlighted the advantages of polymer-based systems in terms of corrosion resistance and long-term durability.

Despite the aforementioned developments, conventional concrete pavement systems still face significant maintenance challenges. When localized damage occurs within a pavement slab, large sections of the pavement often need to be removed and replaced to avoid stress concentration at the joints. This process leads to increased construction time, higher maintenance costs, and excessive material waste. Removable or demountable pavement systems offer a promising solution by allowing individual slabs to be replaced without disturbing adjacent panels. However, limited research has been conducted on removable dowel bar systems capable of providing both effective load transfer and easy slab replacement. Therefore, the present study aims to develop and experimentally evaluate a demountable GFRP dowel bar system incorporating steel and FRP ring confinement elements in precast concrete pavements in order to improve load transfer efficiency, reduce stress concentration, and enhance pavement maintainability. The particular research objectives of this study are:

- To suggest and design a new removable dowel system with the combination of GFRP bars and polymer rings to decrease the stress concentration in the boundaries between the slab and dowel.
- To experimentally propose to study the structural behavior of the proposed system in both monotonic and cyclic loading conditions by using full-scale specimens.
- To compare the performance of the proposed GFRP system to the conventional steel dowel systems in terms of load transfer behavior, cracking response, stiffness, and failure mode.
- To assess the usefulness of polymer rings in enhancing the spread of stress and maximizing the eventual load-bearing capacity of the joint.
- To determine the demountability and maintainability of the proposed system in terms of slab replacement and reduction of material waste.

The main purpose of connecting detachable rails is to allow for the installation, maintenance, and replacement of each paving slab independently without affecting other pavement units. Installing a GFRP dowel bar into a single pavement slab is the first stage of the installation procedure. The uncovered end of the dowel bar is placed into a pre-formed top slot in the adjacent slab after it has been positioned. A small plastic sheet that protects the slot and is simple to remove when needed is placed over the top slot once the dowel bar has been positioned correctly. When replacing a pavement slab, the damaged slab must be lifted, the dowel bar must be removed, and a new slab must be installed in its place. Additionally, the GFRP dowel bar itself may be easily withdrawn and replaced by simply raising the neighboring slab and inserting a new dowel bar if it becomes broken or deteriorates over time. This ensures system lifetime and ease of maintenance. Fig. 1 illustrates the parts of the slab and Fig. 2 shows the detailed layout inside the concrete block.

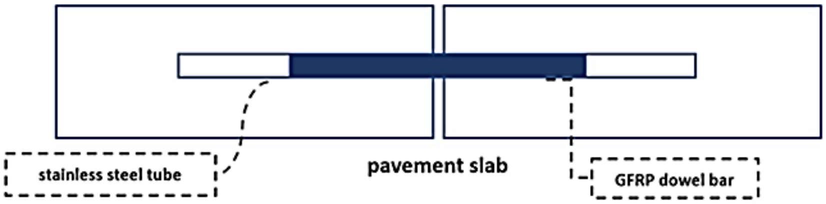

Fig. 1. Stainless steel pipe overlap with GFRP dowel bar

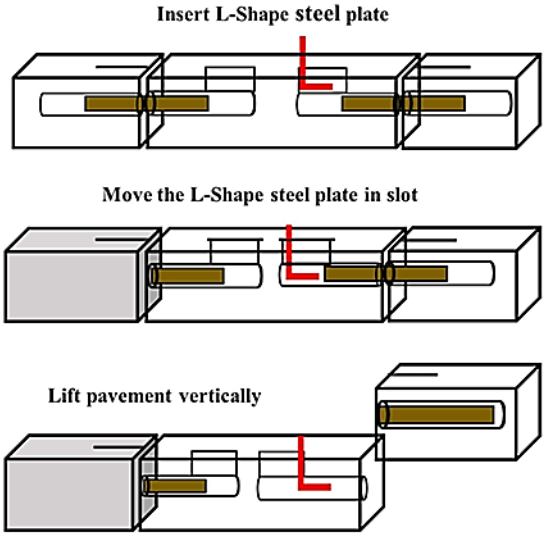

Fig. 2. Demountable mechanism

2. Experimental Program

This study aimed to experimentally analyze the structural performance and viability of the removable dowel system in precast concrete pavements using GFRP dowel bars. Seven beam specimens were made and tested based on the updated version of the AASHTO T253 test specification to provide consistency and results comparison. A two-specimen was made as a reference for a standard epoxy-coated steel dowel bar as an example of the traditional joint system. The rest of the five specimens were developed as removable systems with a combination of GFRP dowel bars and the various confinement arrangements, with an aim of examining how the proposed demountable concept affects the load transfer behavior and response of the structure. The dimensions of reference for the specimens were 200 mm x 300 mm x 1150 mm in general. Out of the removable sample, three of the beams were made of the same size as the reference specimen and with either steel rings or GFRP rings attached besides a stainless-steel sleeve, which was added so that the dowel could move relative to the concrete around and that the slab could be replaced in the future. Additionally, the cast of two further specimens with the same height and length but with a bigger section width was carried out to examine the effects of the size of specimens on the load-carrying capacity and the stress distribution around the dowel-concrete interface. Figs. 3 and 4 show the structure of the specimen and the key stages of the sand pavement slab casting process.

3. Materials Properties

3.1. Steel and GFRP dowel bar

According to modified AASHTO guidelines, the steel dowels used in this study had dimensions of 450 mm in length and 25 mm in diameter. A 34 mm outer diameter stainless steel tube was used to cover the GFRP dowels. To stop corrosion and weaken their bond with the concrete, a thin layer of epoxy was applied to the steel dowels. The manufacturer's tests, which included comprehensive mechanical properties, were used to validate the properties of GFRP.

3.2. Normal strength concrete

The pilot project took place at the Structural Engineering Laboratory of Al-Qadisiyah University. Normal-strength concrete was employed in the casting of each specimen, while ASTM C192 was used for mixing, placing, and curing of specimens. Subsequently, the specimens were numbered and approved, with approval gained after 28 days of curing for testing. In addition, mechanical testing was performed to certify conformity to concrete specifications. Workability and compressive strength were measured through cube compression and shrinkage tests; average compression is noted as 29.7MPa. Fig. 5 shows the casting of cubes and testing of cubes.

3.3. Specimen preparation and casting

Concrete pavement joint specimens were cast to simulate transverse joints in rigid pavements. Each specimen consisted of two adjacent concrete slabs connected through a demountable dowel bar system located at the joint interface. The dowel bars were positioned at mid-depth of the slabs to replicate field conditions. The ring systems were installed around the dowel bars at the joint region to enhance load transfer and control bearing stress. After casting, all specimens were cured under controlled laboratory conditions for a 28-day period before testing.

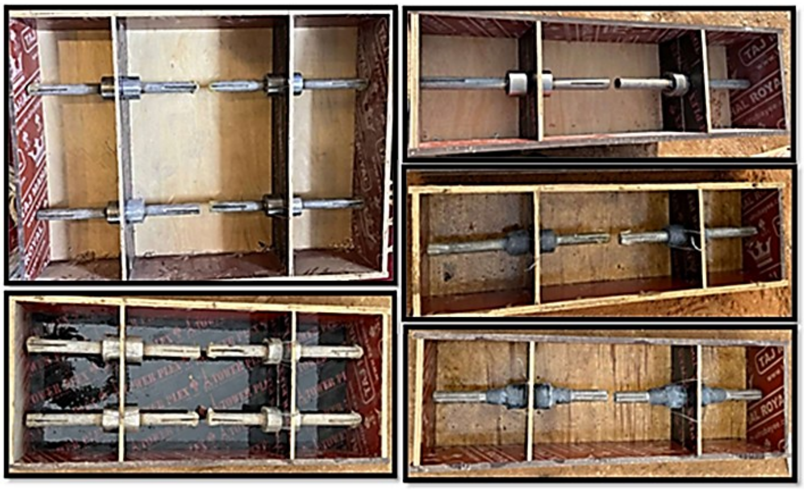

Fig. 3. Preparing the molds before pouring

Fig. 4. Spacemen’s casting

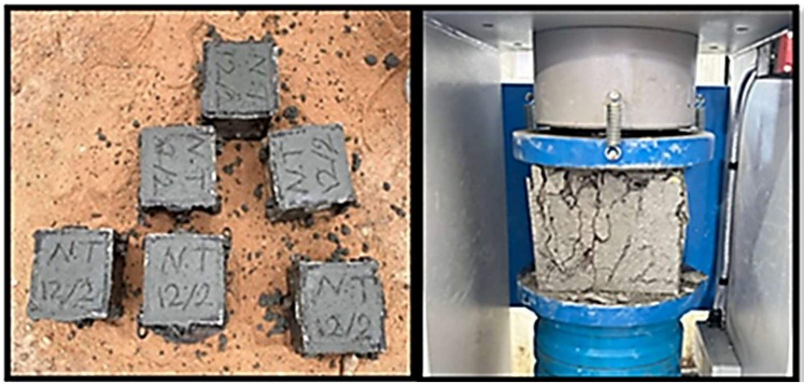

Fig. 5. Casting and testing cubes

4. Test Methodology

The seven research specimens were subjected to testing by a large apparatus that has a loading capacity of 1000kN under monotonous loading. To make conditions close to reality, they were positioned on a supported frame. Thus, a hydraulic actuator was used vertically so that a distributed load would be applied 3 inches from the edge on the left side and from the right side in the middle slab until failure. A Linear Variable Differential Transducer (LVDTs) was used in the middle of the middle concrete specimen to accurately gauge displacement under loading conditions. Before testing, gauges were calibrated to company standards and checked experimentally. Then, to avoid any noise and dislocation to signal acquisition, gauges were established to be properly connected to the acquisition during acquisition. The loading was the same for each specimen during each application, with only 1 variable - the speed of loading application (2mm/min) - set to the same statistic on each occurrence for better reliability. Fig. 6 shows the testing machine with the specimen.

Fig. 6. The testing machine with the specimen

5. Results and Discussion

5.1. Failure mode

The observed failure modes were primarily governed by the mechanical properties of the GFRP dowel bars and the level of confinement provided by the adopted ring systems. In general, GFRP dowels are characterized by high tensile strength and relatively low ductility, which results in a predominantly brittle fracture once the tensile capacity is exceeded. Specimens incorporating double FRP ring systems exhibited a more gradual, progressive failure mode than other configurations. The increased confinement provided by the two FRP rings delayed damage initiation and promoted a gradual accumulation of internal fiber rupture. Failure typically initiated locally within the dowel cross-section and propagated progressively as fiber breakage increased. As a result, these specimens could sustain higher tensile loads, reaching peak values of approximately 58–60kN, while exhibiting reduced overall deformation at failure 7.5–8.0 mm. This dispersed fracture mechanism indicates an enhanced ability of the system to control damage evolution. Specimens fitted with a single FRP ring showed more abrupt failure behavior. Upon reaching the ultimate load of 52kN, the GFRP dowel fractured almost instantaneously, as evidenced by a sudden drop in load-carrying capacity. Specimens incorporating steel ring systems demonstrated a semi-ductile response. Although the GFRP dowel itself failed in a brittle manner, the presence of the steel ring allowed for localized plastic deformation within the confinement system. This resulted in partial stress redistribution before failure, reducing the sudden loss of load capacity and producing a more stable post-peak response compared to FRP ring specimens, with a slight increase in overall ductility. The reference specimens with steel dowel bars exhibited relatively high peak loads 89–91kN; however, failure was mainly governed by severe concrete crushing around the dowel region rather than dowel fracture. Following peak load, these specimens showed poor post-failure performance, indicating that the collapse mechanism was controlled by concrete damage rather than controlled dowel behavior. Overall, the results clearly demonstrate that increased confinement, particularly using double FRP rings or steel rings—significantly enhances the structural robustness of the connection system by transforming the failure mode from a sudden brittle fracture to a more delayed and progressive response. Typical failure patterns of the steel and GFRP dowel specimens are illustrated in Figs. 7 and 8.

5.2. Load-displacement behaviour

Besides a qualitative examination of the load- displacement curves, a more analytical approach can be based on the stiffness, peak load, and nonlinear behavior of the experimental specimens. The first linear section of the curve reflects the elastic response of the system, where the combined stiffness of the GFRP dowel and enclosure of the steel tube around and rings control the global stiffness. The specimens having two rings had a stiffer initial slope, meaning that they were stiffer laterally, which proves the usefulness of higher confinement in preventing dowel rotation and local bearing deformation in the surrounding concrete. An increase in the applied load, a gradual loss of linearity was observed, and may be explained by the factual development of micro-cracking in the concrete and the rise of local contact stresses at the dowel sleeve interface. One can analytically explain the higher peak loads observed in the specimens that had double FRP rings greater than 60 kN by the fact that more of the dowel capacity can be mobilized since the redistribution of the stress along the embedded length of the dowel is improved, therefore, eliminating the stress concentration at the critical section. Moreover, the general pattern of the load-displacement curves suggests that the containment system has a leading role in regulating the structural reaction of the connection. Adding more and more confinement (i.e., with the help of the use of double rings, but not single rings) clearly leads to the fact that both lateral rigidity and the load-carrying capacity become much better; it can be seen that the mechanical characteristics of the offered system are determined not only by the dowel material itself but also by the effectiveness of the containment and stabilization system in which the dowel material is incorporated. A similar experimental trend was reported by Guo et al. [32] in their investigation on stainless steel ring-strengthened removable dowel bar connection systems. Their experimental results demonstrated that specimens incorporating stainless steel rings achieved improved load-carrying capacity and stiffness compared to unconfined specimens. The stainless-steel ring acted as an effective confinement element, reducing localized concrete crushing and delaying crack initiation at the dowel–concrete interface. The failure modes reported by Guo et al. [32] further indicated that ring-strengthened specimens exhibited a more gradual and controlled damage evolution, whereas unconfined specimens were dominated by localized concrete damage and abrupt stiffness loss. This behavior is consistent with the experimental trends identified in the present study. Although the confinement technique employed by Guo et al. [32] utilized stainless steel rings, the agreement between both experimental studies ascertains that the key performance enhancement mechanism is the provision of effective confinement around the dowel region rather than the material form of the confinement element itself. Overall, the consistency between the experimental findings of the present study and those reported by Guo and Chan reinforces the conclusion that confinement-based strategies are essential for improving the structural performance, durability, and reliability of removable dowel bar connection systems. Fig. 9 presents the load–displacement curve of the reference model, while Fig. 10 illustrates the curves for specimens with widths of 300, 400, and 800 mm using steel rings. Fig. 11 shows the curve for the 300 mm specimen with an FRP ring, and Fig. 12 provides a comparative graph of load–displacement behavior between specimens with different ring types.

5.3. Toughness

The toughness results of the pavement specimens, displayed in Fig. 13, demonstrate that the dowel bar material and confinement configuration significantly affect the energy absorption capacity. The reference slabs with steel dowels produced higher toughness values than the GFRP-doweled slabs, which showed moderate toughness values that considerably increased with the addition of FRP confinement rings. Adding one or two steel or FRP rings improved the performance of the GFRP samples, indicating that restraint is a useful technique for compensating for the inherent flexibility of GFRP screws. The size effect is lower stiffness values for larger samples, but relatively the same stress values are recorded. Therefore, it seems sample geometry and reinforcement material play a role in assessing performance.

Fig. 7. Steel dowel bar failure

Fig. 8. GFRP dowel bar failure

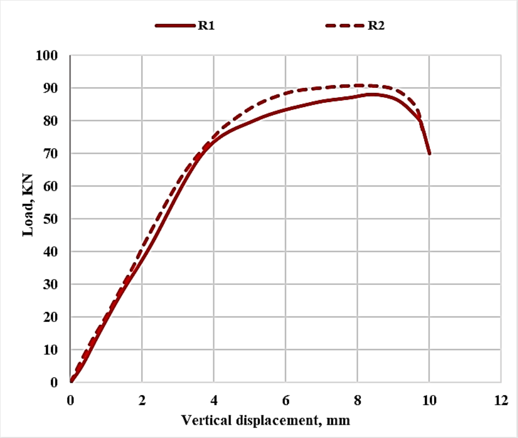

Fig. 9. Graph of load displacement for the reference model

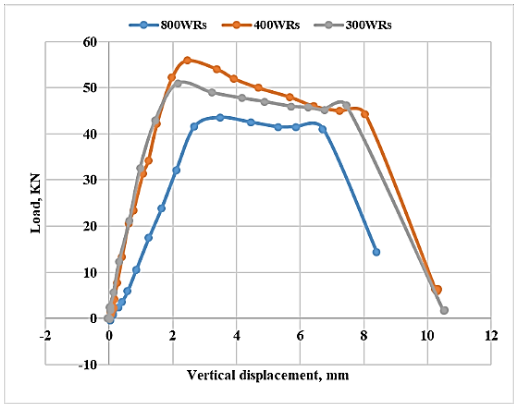

Fig. 10. Load displacement curve for 300, 400, 800 mm widths with steel ring

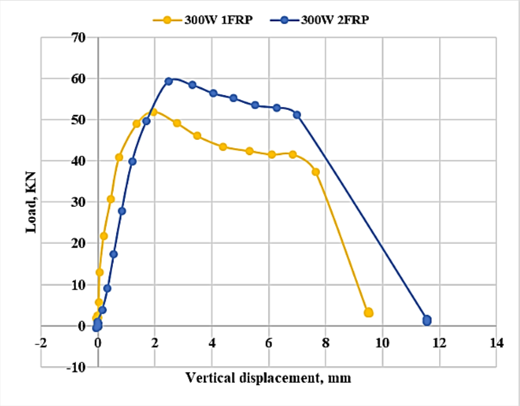

Fig. 11. Load displacement curve for a 300mm width with FRP ring

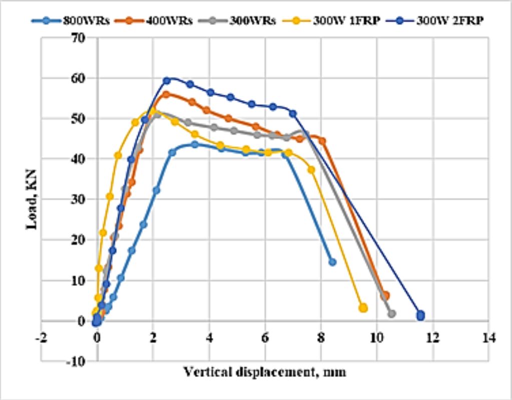

Fig. 12. Graph of load displacement for comparison between Samples with different rings

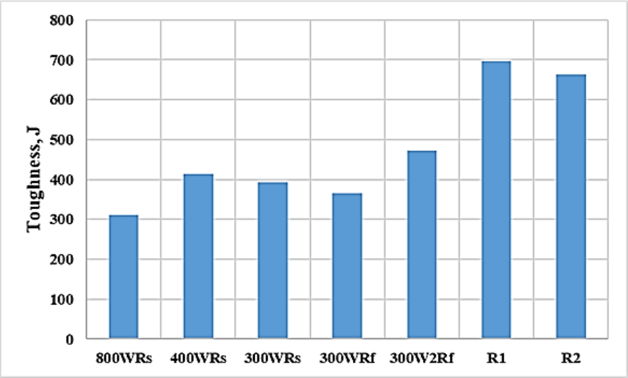

Fig. 13. Results of toughness

6. Conclusions

This paper suggested and experimentally tested a removable GFRP dowel-based anchoring system on the pavements with jointed precast concrete with the aim of enhancing maintainability, durability, and performance of load transfer. The experimental outcomes proved that the suggested system can offer high structural performance and allows full demountability, which makes it possible to change the slabs accurately and minimizes material waste during maintenance processes. Since the GFRP dowel bars are more flexible than the standard steel dowels, this property does not affect the overall system performance. However, the advantages that come with the use of GFRP, including corrosion resistance, ease of handling, and increased durability, at least outweigh these disadvantages, especially in aggressive environments. Economically, although the proposed system might have a higher initial cost since it involves the use of GFRP material and stainless-steel sleeves, the long-term operation of the system reveals that the extra cost is compensated by massively lower maintenance needs and longer service intervals. The GFRP system, unlike steel dowels, is less prone to corrosive decay, and hence the deterioration of the system is minimal over time, limiting the deterioration of the structure at the joints. In general, the suggested removable GFRP dowel system has great potential as a sustainable and resilient solution in the case of precast concrete pavements, providing better durability, simpler maintenance, and an extended period of functional life. The research suggested the necessity to establish the long-term fatigue performance, elaborate a finite element model to study the slab-dowel interface, and assess the effects of environmental conditions on the system behavior in the long-term, including temperature and moisture.

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