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THE FIRST APPLICATION OF ULTRA-HIGH PERFORMANCE CONCRETE LINK SLAB IN MALAYSIA

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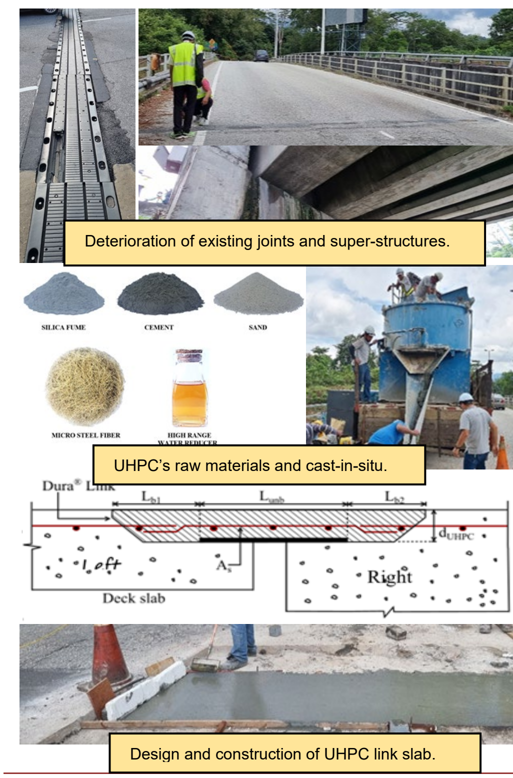


Abstract

Conventional expansion joints in road bridges often suffer from issues like leakage, debonded seals, concrete damage, and short service life. To address these problems, a solution involving flexible link slabs using normal strength concrete (NSC) was proposed. While this method can enhance serviceability and reduce maintenance costs, it lacks durability and tensile strength. Recent interest has focused on cast-in-situ ultra-high performance concrete (UHPC) link slabs due to their exceptional mechanical properties, early strength, durability, ductility, and energy-absorption capabilities. However, there is limited information on their field implementation. To address this gap, a pilot UHPC link slab was designed and implemented to replace a damaged bituminous plug expansion joint in a Malaysian road bridge. The pilot link slab followed New York State Department of Transport (NYSDOT) guidelines and used a high early strength UHPC mix with minimal shrinkage through the combination of expansive agents and shrinkage-reducing admixture (SRA). Monitoring the project over two years has shown no performance concerns with the UHPC link slab. This paper provides a comprehensive overview of the construction process, along with experimental results on the mechanical properties and shrinkage characteristics of the new UHPC.

Keywords: Ultra-high-performance concrete, Link slab, Durability, Expansion joints, Bridge

1.0 INTRODUCTION

Bridges are subjected to dynamic forces, temperature fluctuations, and structural movements that can lead to stress, deformation, and deterioration. Expansion joints play a critical role in accommodating these forces by allowing controlled movement and deformation while maintaining structural integrity [1], [2]. Expansion joints are engineered devices that bridge the gap between adjacent bridge segments, accommodating movements caused by factors such as temperature changes, seismic activity, and differential settlement. Their effectiveness is vital in preventing excessive stress and deformation that could lead to structural damage or failure. The proper selection, design, and installation of expansion joints are crucial to ensure the overall performance and safety of bridges. Assessing the performance of expansion joints involves monitoring their ability to accommodate movements, endure environmental exposure, and resist wear and tear. Over time, exposure to harsh weather conditions, vehicular traffic, and corrosive agents can lead to deterioration and reduced functionality of expansion joints [3]–[6]. Regular inspection, maintenance, and repair are essential to extend their service life and prevent disruptions to bridge operations. Despite their critical role, expansion joints pose challenges such as water infiltration, debris accumulation, noise generation, and maintenance difficulties. Researchers and engineers continue to explore innovative materials, designs, and technologies to address these challenges and improve the overall performance of expansion joints. Additionally, the integration of smart sensors and monitoring systems holds promise for real-time assessment of expansion joint condition and performance [7]–[9].

Expansion joints on bridge not only have to allow for thermal, shrinkage and creep movements, they also have to bridge the gap on the road deck so that cars can safely drive over it. There are many creative methods to manage thermal expansion and the gap, however, short service life and costly maintenance are the most common concerns about the past proposed methods [10]–[12]. As shown in Figure 1, offset of deck slab and damage to joint seals, spalling and loss of steel armouring as well as low comfort to traffic are some common challenges of the existing expansion joint devices. Figure 2 shows corrosion and concrete spalling on beam ends, piers and pier caps resulting from water passing through damaged expansion joints of the bridges in USA [13].

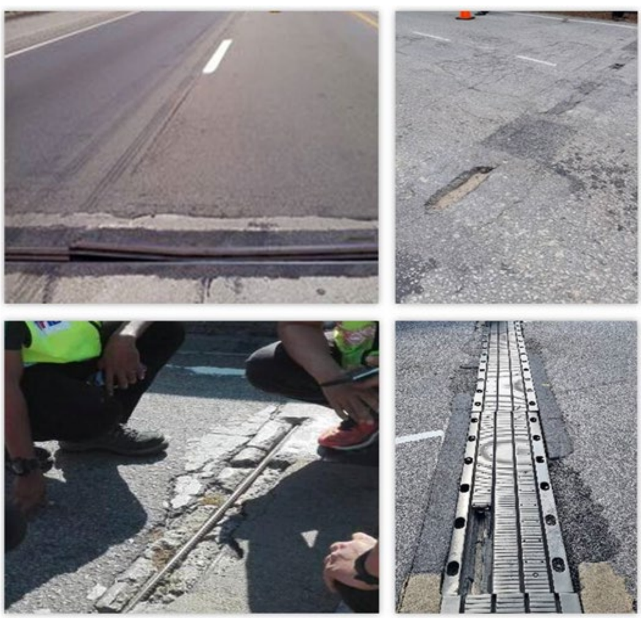


Figure 1 Conventional bridge joints deterioration, from Public Works Department (JKR) Malaysia

Figure 2 Corrosion and concrete spalling due to leaking joint [13]

Application of flexible link slab continuous over piers using cast-in-situ normal strength concrete (NSC) was proposed to eliminate bridge deck joints and increase service life of the bridges. However, low durability, brittle behaviour, low bond and low tensile strength of NSC required regular monitoring and maintenance.

Advancements in the concrete industry have led to the development of a new cementitious composite product called ultra-high performance concrete (UHPC) [14], [15]. UHPC is able to deliver remarkable fresh and hardened properties that far exceed conventional concrete properties [16]. Recently, field-cast UHPC link slab has captured the attention of engineers, owners and contractors across the world. This technique can be simpler to construct and also provide longer service life with negligible maintenance than conventional methods (i.e. expansion joints devices and NSC link slab).
New York State Department of Transportation (NYSDOT) published a guideline and example design procedure which is available online in 2017 [17]. Since then more than 25 UHPC link slabs designed and constructed in USA.

In this study, an in-depth exploration of the design calculations, mechanical properties, and construction procedures related to UHPC link slabs is provided. This research serves as a pilot project that will be implemented in the Gombak District, Selangor, Malaysia, aiming to bridge the knowledge gap and provide valuable insights into the utilization of UHPC for enhanced bridge infrastructure. Readers can expect a comprehensive understanding of the benefits and practical considerations associated with UHPC link slabs, with a specific focus on their application in the Malaysian context.

2.0 METHODOLOGY

2.1 Overview of UHPC Link Slab Project

Conventional expansion joints and UHPC link slabs differ significantly in their mechanical behavior. Conventional expansion joints are typically made of elastomeric materials or metal components with limited load-bearing capacity, primarily accommodating small temperature-related movements. They are less durable, require frequent maintenance, and may deteriorate over time. In contrast, UHPC link slabs are constructed from ultra-high-performance concrete, known for its exceptional strength, durability, and load-bearing capacity. UHPC link slabs can handle heavy loads and a broader range of movements, including horizontal, vertical, and rotational. They are highly durable, require minimal maintenance, and are resistant to environmental factors, offering a longer service life. UHPC link slabs also contribute to reduced noise and vibrations on bridges. These differences make UHPC link slabs a preferred choice for modern bridge construction where extended service life and superior performance are essential.

The first UHPC link slab was designed and successfully implemented to replace a damaged bituminous plug expansion joint of a road bridge in Gombak District (FT68B, Section 3.35), Selangor, Malaysia in February 2022 (GPS Location: 3.249040, 101.730701). The selected site for the pilot project was found to be suitable with minimal expected impact on traffic. It is a double span (28m + 28m) with two-lane, one-way road bridge as shown in Figure 3. Hence, it is possible to close one lane to traffic, constructs the first half of the link slab and reopen the lane to traffic. The process will then be repeated on the other lane (second half of the link slab). The span length of the bridge is 28m with a total width of 8.55m.

Figure 3 A two-lane, one-way road bridge for pilot link slab (GPS Location: 3.249040, 101.730701)

The existing bituminous plug is visibly deteriorated with deep holes, slight settlement and cracks around expansion joint despite this joint was repaired six months earlier (see Figure 4a). As shown in Figure 4b, water ingress through damaged expansion joints caused mould and moss. The presence of mould and moss is a concern, as it shows the bridge had become moist enough to support the growth of biofilm, some of which can cause bio-deterioration [18]. However, from visual inspection, the existing concrete deck is in fair condition, which makes it suitable for the construction of a link slab. Figure 5 demonstrates the construction methodology of the first UHPC link slab in Malaysia.

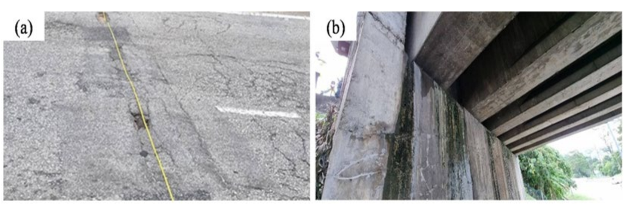
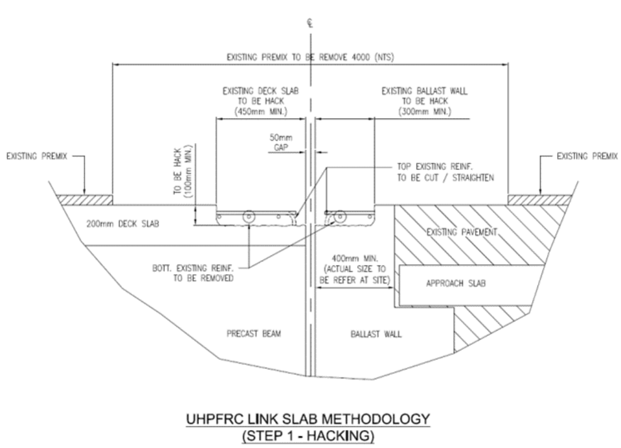


Figure 4 (a) Deterioration of existing bituminous plug, and (b) water ingress to beam end and substructure



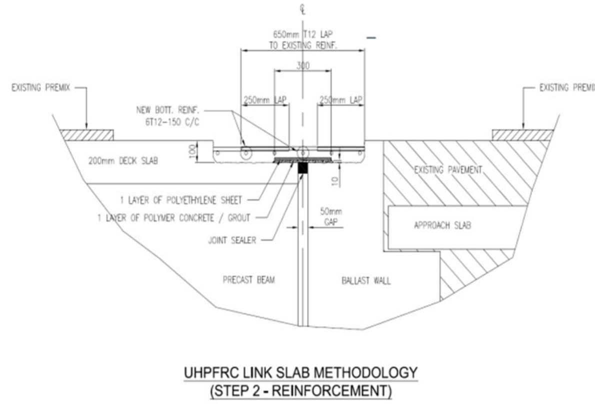


Figure 5 The pilot UHPC link slab methodology

2.2 UHPC Link Slab Design

Figure 6 illustrates the schematic diagram of a pilot UHPC link slab called Dura® Link. The link slab has an overall length of 9m with a total width of 0.8m and a standard thickness of 100mm as shown in Figure 7. The pilot link slab was designed according to New York State Department of Transport (NYSDOT) design procedure and example for UHPC link slabs [17]. Based on NYSDOT analysis that considered the distribution of strain due to girder end rotation, it was found that all translation will occur at the bearings. The force required to strain the UHPC in pure tension is extremely large and even a typical fixed bearing will displace long before generating enough force to elongate the UHPC. Therefore, the link slab design assumes that the UHPC section is subject to bending only [17].

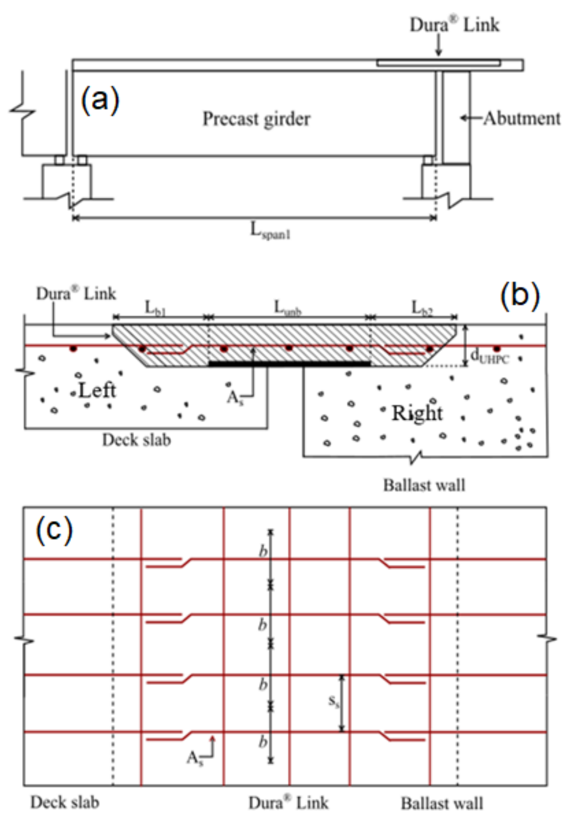


Figure 6 Schematic diagram of the pilot UHPC link slab

Due to the presence of high amount of micro steel fibers (2.5% by vol.) in UHPC, conventional steel reinforcement is not required within the UHPC link slab for strength. However, as suggested by NYSDOT design example, one layer of longitudinal reinforcement can be provided in the center to improve the overall toughness of link slab. The size, spacing, and type of steel bars should match that of the adjacent concrete deck. Therefore, 16mm diameter steel bars (b = 150c/c spacing) with area (A_s) of 113mm^2, yield strength (f_y) of 460MPa and elasticity modulus (E_s) of 200GPa were utilized at longitudinal direction as shown in Figures 6b & 6c. Further, in this project, 5T16-150 c/c were used at transverse direction to match that of the adjacent concrete deck. A partial link slab depth of d_{uhpc} = 100mm was designed as per NYSDOT design example (see Figure 6b). The total thickness of existing RC deck slab is 200mm.

2.3 Construction Stages

The following briefly gives the construction stages of the link slab.

2.3.1 Site Preparation

Temporary traffic signs, barriers, flagmen and traffic safety officer deployed to control traffic flow. Then, the left lane (see Figure 3) was closed to traffic to replace the first half of the damaged bituminous plug expansion joint (left lane: 0.8m × 4.5m × 0.1m). All materials, manpower and equipment were provided at the site. The area was cleared of all debris, materials or other obstructions before commencement of work.

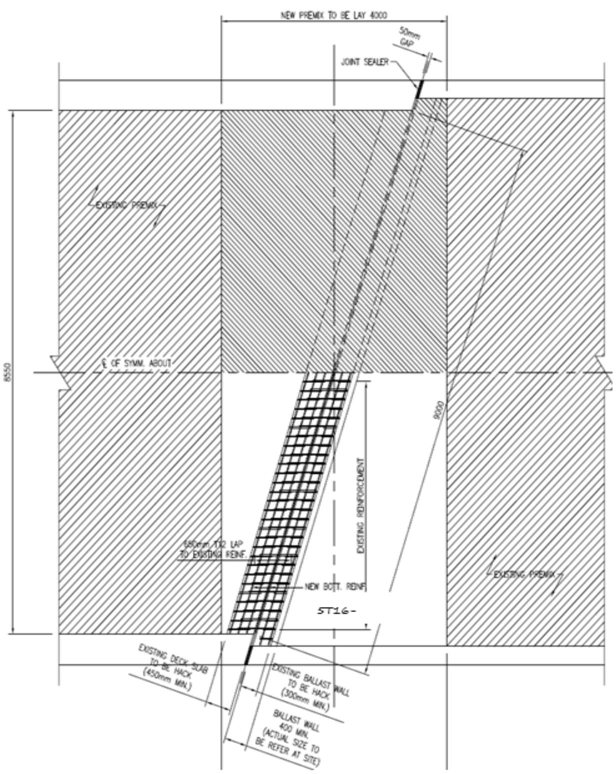


Figure 7 Dimensions and steel bar arrangement

2.3.2 Cutting and Hacking Works

Firstly, the cutting and hacking areas clearly marked. The bituminous plug, asphalt wearing course and about 100mm of the existing bridge deck and ballast wall (see Figure 6b) were removed using a wheel cutter machine and hacking machines as shown in Figure 8.

Figure 8 Marking and hacking of bridge deck and ballast wall with 0.8m (width) x 4.5m (length) x 0.1m (depth)

2.3.3 Construction of Unbonded Zone

The hacked area was cleaned off any loose leftover concrete using a vacuum cleaner (see Figure 9a). A closed-cell foam joint sealer (50mm × 50mm × 4.5m) was utilized to close the 50mm expansion joint as presented in Figure 9b. A layer of grout (about 5mm thick × 300mm wide) was applied on the designated debond zone (see Figure 9c). After the grout surface hard enough, a bond breaker using rubber sheet (6mm × 300mm × 4.5m) was placed to create a debonded zone on the link slab as depicted in Figure 9d.

Figure 9 Construction stages of debond zone: (a) cleaning debris using vacuum, (b) installation of closed-cell foam sealer, (c) place a layer of grout at debond zone and (d) placement of a 6mm thick rubber sheet

2.3.4 Reinforcement Arrangement

Figure 10 shows the reinforcement arrangement in the link slab. As can be seen in this Figure, steel bars T16–150 c/c were used at longitudinal and transverse directions of the bridge to match that of the adjacent concrete deck and abutment in order to improve the overall toughness of the link slab.

Figure 10 Reinforcement arrangement in the UHPC link slab

2.3.5 Link Slab (Casting, Curing, Finishing and Monitoring)

$0.5m^3$ mobile panmixer was employed for mixing DURA® UHPC premix, recognized for its exceptional early strength and minimal shrinkage. This mixture contained 2.5% by volume of straight steel fibers with tensile strength more than 2800MPa, a diameter of 0.2mm and lengths of 13mm and 20mm. To maintain the desired temperature of the fresh UHPC during mixing and placement, a combination of water and ice flakes was employed, as depicted in Figure 11b, ensuring it not exceeds more than 27°C. Controlling the temperature of fresh UHPC within the range of 22 ± 5°C can effectively minimize early-stage cracks. To create the essential surface texture between the UHPC and the wearing course layer, a spiked roller brush was employed (refer to Figure 11c). The exposed surface was covered with curing compound and plastic sheet immediately after placement to prevent surface dehydration as illustrated in Figure 11c-11d. The compressive test was conducted after a 24-hour curing period to achieve a minimum strength of 80MPa. Figure 11e shows the UHPC link slab after the curing process. Subsequently, the road premix team laid and compacted the wearing course on the left side of the UHPC link slab to align it with the adjacent pavement level, as illustrated in Figure 11f. Following this, the left lane was opened for traffic, and the same construction procedure was repeated to replace the second half of the damaged bituminous plug expansion joint (refer to Figure 3) in the right lane, with dimensions of 0.8m × 4.5 m × 0.1m. Figure 11g displays the link slab after the construction process has been completed.

Nail-shaped indicator tools were installed on both the deck and ballast walls of the bridge. Every two months, measurements of relative displacement were taken to detect any potential movements at the superstructure. The initial reference spacing, which was initially set at 240mm on both sides, served as a benchmark for these measurements. In addition to this, the supplier conducted visual inspections to monitor the structural performance of the UHPC link slab during service.

Figure 11 Mixing and curing of cast in-situ DURA® UHPC: (a) $0.5m^3$ mobile panmixer at site, (b) temperature of fresh UHPC around 22°C, (c) spraying curing compound, (d) covering fresh UHPC with plastic sheet, (e) link slab after curing, (f) laying and compacting wearing course and (g) link slab construction completed

3.0 RESULTS AND DISCUSSIONS

3.1 Calculation of Depth of Neutral Axis

As mentioned in NYSDOT design guideline, the link slab is designed for flexural only and assumed that stresses equally distributed within debonded length (see Figure 12).

For design purposes in this research, the modulus of elasticity, maximum allowable compressive stress and maximum allowable tensile cracking strain of UHPC shall be taken as $E_{c,uhpc}$ = 55GPa, $f_{uhpc.c.all}$ = 96.6MPa and $\varepsilon_{uhpc.t.all}$ = 0.0035, respectively. In addition, UHPC tensile cracking stress assumed as $f_{uhpc.t.all}$ = 8.3MPa.

As shown in Figure 6b, total width of link slab, L_{link} calculated as follows:

$$L_{link} = L_{b1} + L_{unb} + L_{b2} = 325 + 300 + 175 = 800 \text{ mm} \quad (1)$$

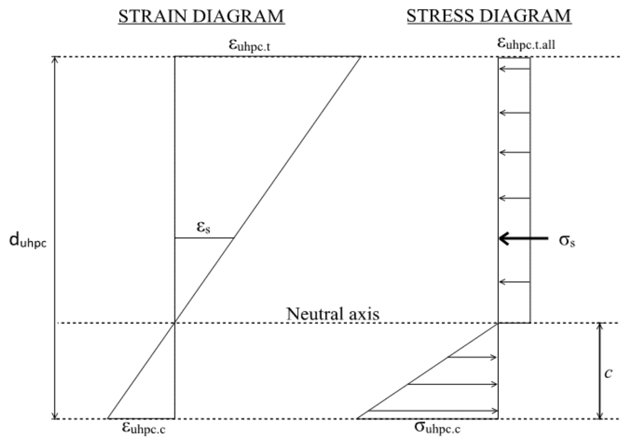


Figure 12 Strain and stress diagrams distribution within debonded length of link slab [17]

where, L_{b1} is the bonded length of UHPC with existing concrete at deck slab (left side), L_{unb} is the unbonded length of UHPC with bond breaker and L_{b2} is the bonded length of UHPC with existing concrete at abutment (or ballast wall at right side). In this study, L_{span1} is the length of the girder (Figure 6a) which is 28m and maximum allowable deflection at midspan for this girder is equal to Δ_{LL1}= girder span/800 = 35mm.

Girder end rotation, ϴ is determined as:

$$\theta = 1.75\frac{2\Delta_{LL1}}{0.5L_{span1}} = 1.75\frac{2\times35}{0.5\times28000} = 0.00875 \;\; radian \qquad (2)$$

In which, ε_{ci} is an assumed UHPC compressive strain due to rotation, and from equation solver, depth of neutral axis, c is calculated as follows:

$$c = \frac{\sqrt{A_s^2 \cdot E_s^2 \cdot \varepsilon_{ci}^2 + (\varepsilon_{ci} \cdot E_{c,uhpc}) \cdot A_s \cdot E_s \cdot b \cdot d_{uhpc} \cdot \varepsilon_{ci} + b^2 \cdot f_{uhpc.t.all}^2 \cdot d_{uhpc}} + b \cdot f_{uhpc.t.all} \cdot d_{uhpc} - A_s \cdot E_s \cdot \varepsilon_{ci}}{b \cdot (\varepsilon_{ci} \cdot E_{c,uhpc}) + 2 \cdot b \cdot f_{uhpc.t.all}} \qquad (3)$$

= 29.34 mm

3.2 Design Check

To finalize the design of the UHPC link slab, the following actual design parameters are checked to be less than allowable design parameters as follows:

$$\varepsilon_{uhpc,t} = \frac{\theta.(d_{uhpc}-c)}{L_{unb}} = 0.0021 \quad < \varepsilon_{uhpc,tall} = 0.0035 \qquad (4)$$

$$\varepsilon_s = \frac{\theta.(\frac{d_{uhpc}}{2}-c)}{L_{unb}} = 0.0006 \qquad (5)$$

$$\sigma_s = \varepsilon_s . E_s = 120 \; MPa \;\; < f_y = 460 \text{ MPa} \qquad (6)$$

$$\varepsilon_{uhpc,c} = \frac{\theta.c}{L_{unb}} = 0.0009 \qquad (7)$$

$$\sigma_{uhpc,c} = \varepsilon_{uhpc,s} . E_{c,uhpc} = 47.07 \; MPa \quad < f_{uhpc,call} = 96.6 \text{ MPa} \qquad (8)$$

where, $\varepsilon_{uhpc,t}, \varepsilon_s, \sigma_s, \varepsilon_{uhpc,c}$ *and* $\sigma_{uhpc,c}$ are the actual values of tensile strain in UHPC, tensile strain in steel bar, tensile stress in steel bar, compressive strain in UHPC and compressive stress in UHPC, respectively due to girder end rotation.

Finally, the design analysis was passed as below:

$$\varepsilon_{uhpc,tall}/\varepsilon_{uhpc,t} = 1.70 \; > 1 \qquad PASS \qquad (9)$$

$$f_y/\sigma_s = 3.82 \; > 1 \qquad PASS \qquad (10)$$

$$f_{uhpc,call}/\sigma_{uhpc,c} = 2.05 \; > 1 \qquad PASS \qquad (11)$$

In this design procedure, tensile strain in UHPC, tensile stress in steel bars, and compressive stress in UHPC exhibited safety factors of 1.7, 3.82, and 2.05, respectively.

3.3 Mechanical Properties and Shrinkage Test Results of DURA® UHPC

The essential characteristics of UHPC material, such as its mechanical and durability properties, play a vital role in the construction of UHPC link slabs that require minimal maintenance. As a result, a series of tests including compressive, flexural, tensile, and shrinkage tests have been carried out to ensure the quality of the UHPC link slabs being utilized. A high early strength UHPC mix with very low total shrinkage was developed for the pilot link slab. The link slab was cast in two different batches for the left and right lanes (~ 0.5m^3/batch). Table 1 shows the quality assurance/quality control (QA/QC) test results on the mechanical strength of the ambient cured UHPC specimens for both cast in-situ mixes according to French Standard [19], where $f_{cm,cu}$ is the mean cube compressive strength at 1 and 28 days using 100mm cubes. $f_{ctm,el}$ and f_{ctfm} are the mean tensile limit of elasticity and mean post-cracking tensile strength at 28 days, respectively, using prisms of 100mm^2 cross-section by 500mm length. The term $f_{ctm,fl}$ is the equivalent elastic flexural strength which was measured using 100mm^2 prisms under four point test condition [19].

Total shrinkage of concrete is mainly composed of autogenous shrinkage and drying shrinkage. Drying shrinkage is very low in UHPC, however, it exhibits substantial autogenous shrinkage due to the low water-to-cement ratio [20]. According to French Standard [21], UHPC without any heat treatment shall have a total shrinkage amplitude around 700 microstarin. Reported values of UHPC free shrinkage according to ASTM C157 [22] tests are normally more than 700 microstarin. Moreover, ASTM C157 does not capture the volume change in the first 24 hours, which can be very high in UHPC [23].

Hence, in this research, initial measurement began after 8 hours of casting (final setting was achieved and hard enough to remove samples from the moulds) at controlled room temperature (23 ± 2°C) to capture early age shrinkage. Figure 13 shows the free shrinkage result of the developed mix for link slab which contains combination of expansive agent and shrinkage reducing admixture to mitigate volume change in UHPC without heat treatment. Shrinkage was tremendously reduced by 72% and 60% at 1 and 28 days respectively, compared with the original mix.

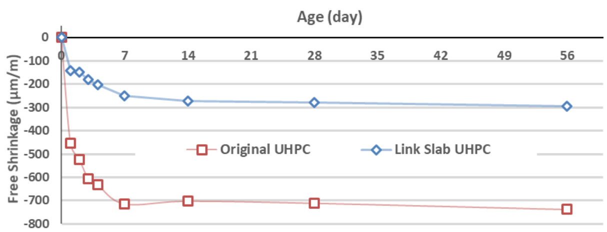


Figure 13 Shrinkage test results of DURA® UHPC mix

Table 1 Material properties of DURA® UHPC link slab (in MPa)

Category	$f_{cm,cu,1d}$	$f_{cm,cu,28d}$	$f_{ctm,el}$	f_{ctfm}	$f_{ctm,fl}$
Mix 1	90.6	155.4	8.6	11.1	29.7
Mix 2	92.0	157.1	8.9	11.6	32.4
Total Nos. of Samples	6	6	12	12	12
Mean Values	91.3	156.2	8.8	11.4	31.1
Standard Deviation, S.D.	1.54	2.18	0.21	0.35	1.91
Student Coefficient	2.015	2.015	1.796	1.796	1.796
Characteristics Values	88.2	151.8	8.4	10.7	27.6

4.0 CONCLUSION

This article showcases the planning, construction, and performance of a pioneering UHPC link slab, which was utilized as a replacement for a deteriorated bituminous plug expansion joint in a Malaysian road bridge. The UHPC link slab's design adhered to NYSDOT guidelines, incorporating a high early strength UHPC mix with minimal shrinkage through the use of an expansive agent and SRA. The study's results underscore the viability of the UHPC link slab approach as a superior alternative to conventional expansion joint methods. This method offers simplicity in construction, enhanced long-term performance, and increased resilience against environmental factors like moisture and chlorides. In summary, the study distinguishes itself by providing empirical evidence of the practicality and long-term performance of UHPC link slabs in bridge construction, aligning with the broader trends in UHPC technology and its applications. It also contributes to the standardization and guideline development for UHPC in bridge engineering. Followings conclusions are drawn as the key findings of the present study:

- The UHPC link slab was designed to accommodate the expected thermal and structural movements of the bridge.
- The UHPC mix was designed to have a high early strength and very low shrinkage, which is important for minimizing cracking and ensuring a good bond between the UHPC link slab and the existing concrete.
- The UHPC link slab was constructed using a wet lay-up method, which is a simple and cost-effective method that can be used in the field.
- The performance of the UHPC link slab has been monitored for two years and there have been no concerns regarding its performance.
- The UHPC link slab method is a viable alternative to conventional expansion joint methods and offers several advantages, such as simplicity of construction, robust long-term performance, and resistance to environmental factors.

Last but not least, the study's findings on a Malaysian road bridge suggest that UHPC link slabs can be a promising alternative to conventional expansion joint methods. However, their generalizability to other regions may be influenced by specific contextual factors, including local climate, construction practices, materials availability, and maintenance requirements. While the UHPC link slab's resistance to environmental factors is an advantage, its long-term performance may differ depending on the unique conditions of each location. Adherence to local design standards and the availability of suitable materials are crucial considerations when contemplating the application of this method beyond the studied context.

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