# Construction of a 50 Metre Long Ultra High Performance Ductile Concrete Composite Road Bridge

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**Abstract** One of the most significant breakthrough developments in concrete technology at the end of the 20th century was that of ultra-high performance 'ductile' concrete (UHPdC) with compressive strength up to 200 MPa and remarkable improvements in durability, ductility and toughness. This paper presents details on the construction of a 50 metre span road bridge using UHPdC. Examples on environmental impact calculations are presented comparing design solutions with that of conventional approaches. The results show, that given the right circumstances, UHPdC structures can be more environmentally friendly than that of the conventional concrete/steel technologies in terms of reduction of $CO_2$ emissions, embodied energy and global warming potential.

## Introduction

The Public Works Department of Negeri Sembilan (Malaysia) first used ultra-high performance ductile concrete (UHPdC) in the construction of a medium traffic road bridge over the Sungai Linggi River, connecting the villages of Kampung Linsum and Kampung Siliau. Construction of the bridge commenced in September 2010 and the bridge was completed in January 2011 (see Fig 1). The bridge was constructed using a single U-trough girder design of 1.75m depth, 2.5m width and was topped with a four metre wide by 200 mm thick cast in-situ reinforced concrete deck slab. The UHPdC girder ends are encased in normal strength concrete abutments at the bridge site and made integral with the abutment seating. The girder was built without any conventional shear reinforcement as the longitudinally prestressed UHPdC had considerable strength in shear, in addition to that of flexure. The UHPdC, with the trade name *DURA*®, was supplied by

Dura Technology Sdn. Bhd and achieved a compressive strength of up to 180 MPa and a flexural strength of up to 30 MPa.

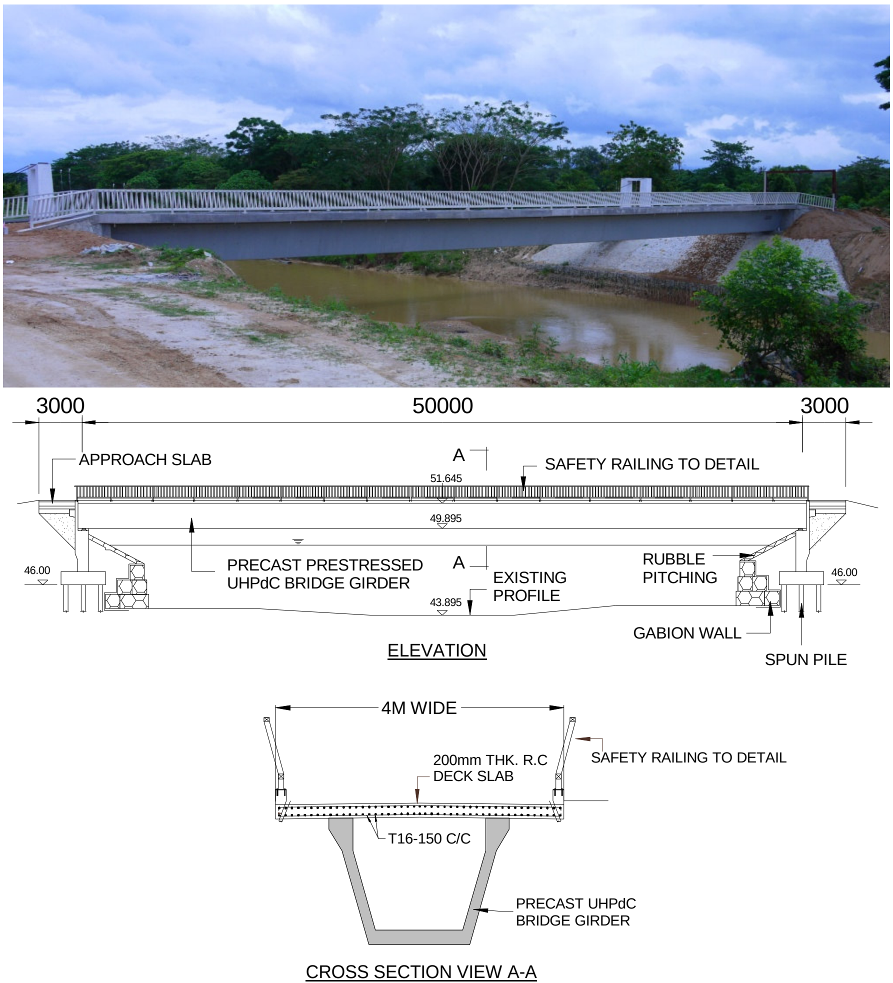



**Fig. 1**. Kampung Linsum Bridge at Rantau, Negeri Seremban, Malaysia.

## Bridge Construction Sequence

The construction sequence is summarized in Table I. The precast girder consists of a total of seven segments that each consist of five standard internal segments (IS) of 8 metres in length and weighing 18 tonnes (each), and two end standard segments (ES), each 5 metres in length and weighing 15 tonnes (see Fig 2). Unlike conventional precast concrete girders, the UHPdC girder does not have vertical shear reinforcement in its thin webs. The only conventional transverse reinforcement used was bursting reinforcement at the anchorage zones, lifting reinforcement at the tendon deflector positions, and dowel shear reinforcement at the top flanges where composite connection with the RC deck is required.

**Table I.** Construction sequence of the superstructure of Kampung Linsum Bridge.

| Step | Activity | Date | Age |
|---|---|---|---|
| **1** | Fabrication of the UHPdC U-girder segments | Mid Oct 2010 | - |
| **2** | Transportation of segments to job site | 15th Nov 2010 | 20 |
| **3** | Assembly of segments | 16th Nov 2010 | 21 |
| **4** | First stage post-tensioning | 23rd Nov 2010 | 28 |
| **5** | Launching of U-girder to abutments | 3rd Dec 2010 | 38 |
| **6** | Casting of in-situ RC deck | 20th, 22nd Dec 2010 | 55, 57 |
| **7** | Second stage post-tensioning | 5th Jan 2011 | 71 |
| **8** | Casting of the composite bridge to the abutment | 13 Jan 2011 | 79 |

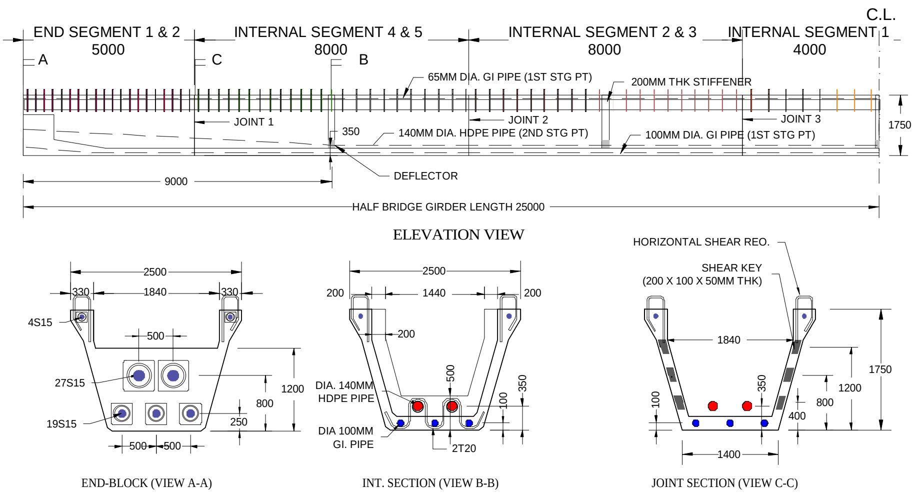



**Fig. 2**. Details of 50 metre span UHPdC bridge.

## *Mechanical Properties of UHPdC*

The UHPdC used in this project is a Malaysian blend with the trade name *DURA*®. UHPdC is a new generation of ultra-high performance construction material suitable for use in the production of precast elements for civil engineering, structural and architectural applications. It is a highly homogenous, cementitious based composite, material without coarse aggregates that can achieve compressive strengths of 160 MPa and beyond. It consists of a unique blend of very high strength micro-steel fibers and cementitious binders combined with very low water content. In addition to its extraordinary strength characteristics, UHPdC has a ductility comparable to that of steel and a durability comparable to that of natural rock.
Table II summarises the mechanical properties of the UHPdC used in the U-girders cast for the bridge. As each segment was cast from different batch of concrete, control samples were taken for all segments.

**Table II**. Mechanical properties of UHPdC.

| **Ref.** | **Segment** | **End** | **Centre** | | | | | **End** |
|---|---|---|---|---|---|---|---|---|
| | | **ES1** | **IS4** | **IS2** | **IS1** | **IS3** | **IS5** | **ES2** |
| | **Cast Type** | **FC** | **MC** | **FC** | **MC** | **FC** | **MC** | **FC** |
| **[1]** | $f_{cu,\,1\,day}$ (MPa) | 85 | 82 | 80 | 89 | 99 | 82 | 100 |
| | $f_{cu,\,28\,day}$ (MPa) | 189 | 180 | 171 | 183 | 188 | 183 | 193 |
| **[2]** | $E_{o,\,28\,day}$ (GPa) | - | - | - | - | - | - | 46.5 |
| **[3]** | $f_{ct,\,28\,day}$ (MPa) | - | - | - | - | - | 6.6 | - |
| | $f_{sp,\,28\,day}$ (MPa) | - | - | - | - | - | 16.0 | - |
| **[4]** | $f_{cr,\,28\,day}$ (MPa) | 14.5 | 15 | 14.0 | 14.5 | 15.5 | 15.0 | 15.5 |
| | $f_{cf,\,28\,day}$ (MPa) | 31 | 30 | 32 | 30 | 32 | 29 | 33 |
| | $I_5$ | 5.95 | 5.86 | 5.52 | 6.00 | 5.81 | 5.94 | 6.22 |
| | $I_{10}$ | 13.4 | 13.9 | 12.5 | 13.4 | 13.7 | 13.7 | 14.4 |
| | $I_{20}$ | 29.9 | 31.4 | 27.7 | 30.1 | 31.1 | 31.3 | 32.6 |

Notes: FC = formed cast; MC = matched cast; ES = end segment; IS = internal segment

The UHPdC achieved a cube compressive strength ($f_{cu}$) of between 80 and 100 MPa after 1 day; and 170 to 190 MPa after 28 days (see Table II). The cube compressive strength was measured according to BS 6319-2 [1] using at least six specimens with dimensions of 100 mm.

Three 100 mm diameter by 200 mm high cylinders were tested to obtain the modulus of elasticity ($E_o$) and the experimental result shows the UHPdC had an average $E_o$ value of 46.5 GPa. The $E_o$ values were determined according to

BS 1881:121 [2] under force control at a rate of 20 MPa/min. The longitudinal strains were obtained using electrical strain gauges.

Four 100 mm diameter by 200 mm high cylinders were tested to obtain the split cylinder, indirect, tensile strength according to BS:EN 12390-6 [3]. The first cracking strength ($f_{ct}$) is defined as the stress level in the UHPdC associated with a point in the stress-strain (or displacement) curve where the assumption of linear elasticity is no longer applicable. The split cylinder tensile strength ($f_{sp}$) is taken as the point where maximum stress developed in the UHPdC after the first crack has formed.

Flexural toughness testing, as per ASTM-C1018 [4], was used to determine the flexural properties of the UHPdC. The tests were conducted on un-notched specimens with a 100 mm square cross-section and a span of 300 mm. A pre-load of 10 kN was applied to the specimens and then unload to zero. This process was used for five cycles and then the specimens were loaded using displacement control at the mid-span at a rate of 0.25 mm/min until the conclusion of the test. The load decreases gradually after the peak load is achieved (i.e. after $f_{cf}$). Experimental results show all the UHPdC control specimens exhibit strain-hardening behaviour after the first cracking ($f_{cr}$) occurred, which was at an approximate mid-span displacement of 0.03-0.05 mm. This strain (or displacement) hardening behaviour is the result of the steel fibers bridging the micro-cracks and limiting the crack propagation. The test results show that the high volumes of steel fibres in the concrete mix help to increase the fracture strength of the composite, thus improving the overall flexural toughness (as represented by the $I_{5,}$ $I_{10}$ and $I_{20}$ indices).

## *Fabrication*

Manufacturing of the UHPdC U-girder began in mid October 2010. Four segments were form cast and three segments were matched cast against the formed cast segments. All the segments were steam-cured for a period of 48 hours at 90 degrees Celsius, as recommended in [5]. Manufacturing of the last segment (i.e. IS1) was completed in early November and Fig. 3(a) shows the seven segments that were trial assembled and inspected in the factory awaiting transportation to the site. The total weight of the full girder was measured at 120 tonnes.

## *Site Assembly of U-girder*

A total of six 12.2 metre long trucks were used to transport the seven segments to the job site. The segments were loaded onto the trucks on 15 November 2010 and arrived on-site the following morning ready for assembly. Figs. 3(b) and 3(c) show the assembly sequence for the girder. Due to the lightness of the segments, just one 45 tonne mobile crane was needed to place the segments. Within a few hours, the girder segments were positioned and ready for first stage post-tensioning (PT).

## *First Stage Post-Tensioning (PT)*

First stage post-tensioning (PT) was carried out by Freyssinet PSC Malaysia on 23 November 2010. Fig. 3(d) shows a technician stressing the girder for the anchorage blocks for the three ducts of 19S15 tendons (bottom role) and the two ducts of 4S15 (top role). The central ducts (i.e. 27S15) were for the second stage PT. The bottom tendons were stressed by a 7000 kN capacity hydraulic jack for a total jacking force of 3890 kN per duct, whereas the top tendons were stressed by a 4000 kN capacity hydraulic jack to a total jacking force of 819 kN per duct. Both ends of the girder were stressed. At the end of the PT work, the mid-span instantaneous hogging deflection was measured to be approximately 10 mm.

## *Girder Launching*

Fig. 3(e) shows the two 160 tonne mobile cranes used to lift the assembled U-girder onto one end of the steel framed transfer girder. This took less than one hour. Fig. 3(f) shows one end of the U-girder securely fastened on the trolley, which was then gradually towed over the river. The whole of the launching process took approximately 5 hours (see Fig. 3(g)). At the end of the day, all the participants and witnesses were satisfied.

## *In-situ Decking*

After the girder was launched, conventional reinforcement and temporary formwork were positioned ready for concreting to the foundation blocks. Prior to concreting, the deflection at the mid-span of the U-girder under its self-weight, relative to the supports, was measured to be approximately 0 mm. That is the girder was almost level. Fig. 3(h) is taken on 20 December 2010 (day 1 of deck casting) and shows the contractor casting the first half portion of the deck. At the completion of the deck concreting, the mid-span displacement was measured to be 25 mm. After day two, the partially completed bridge had undergone an additional 25 mm of sag at the mid-span due to the shrinkage effect from the reinforced concrete deck slab. At this stage the net deflection is approximately 50 mm. On

22 December (day 3), the remaining half of the deck was concreted and the instantaneous mid-span deflection was recorded to be 43 mm, giving a total deflection of 93 mm. On 24 December (day 5), a further mid-span sag deflection of 10 mm was recorded, making the total deflection 103 mm. Prior to the second stage post-tensioning, on 4 January 2011 (day 16), the total mid-span sag deflection was 130 mm.

## *Second Stage Post-Tensioning*

The second stage post-tensioning (PT) was carried out on 5 January 2011. Fig. 3(j) shows stressing of the 2 central 27S15 tendons. Each duct was prestressed to a jacking force of 5265 kN, giving a total prestressing force of 10 530 kN. At the end of the PT work, the internal ducts were examined for defects (see Fig. 3 (k)). Fig. 3(l) shows a close up view of the deflector and visual examination showed the deflectors to be crack free. At this stage, the mid-span instantaneous upward deflection was measured to be approximately 60 mm, giving a net mid-span sagging deflection of 70 mm. Fig. 3(m) was taken a few days later and shows a 22 tonne excavator placed at the mid-span of the bridge. The change in the mid-span displacement for this proof-loading was 7 mm.

(a)

(b)

(c)

(d)


(e)

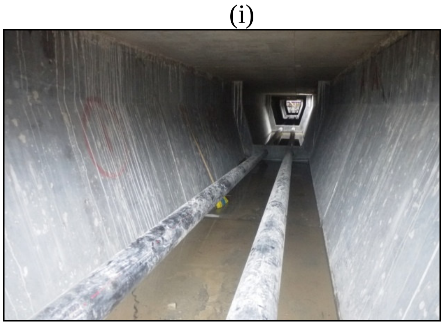

(f)

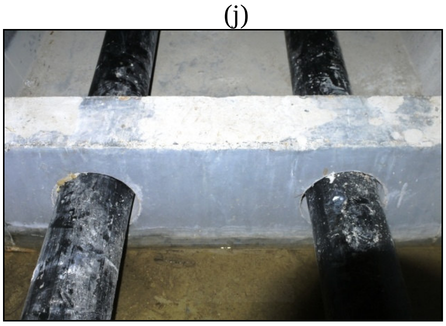

(g)


(h)


(i)


(j)


(k)


(l)


(m)


(n)

**Fig. 3.** (a) Assembly and inspection of girder in factory prior-to transportation to site; (b) and (c) unloading and assembly of the girder segments; (d) 1st stage post-tensioning (PT) of girder; (e) lifting of girder using two 160 tonne capacity mobile cranes; (f) towing the girder over the river using A-frame system; (g) girder launched on the abutments; (h) concreting of RC deck in progress; (i) bridge ready for 2nd stage PT; (j) 2nd stage PT in progress; (k) view of external ducts after PT; (l) no sign of breakage at the deflectors; (m) load proof test using a 22 tonne excavator placed at the mid-span of the bridge; and (n) the completed bridge.

## Environmental Impact Calculation (EIC)

Initially the engineers who were engaged to design the bridge had proposed using two steel structural welded beams (see Fig. 4). Later, the consultants choose to go with the UHPdC girder design due to convincing argument re the benefit of adopting an UHPdC composite bridge design solution. Such benefits include much lower maintenance, more eco-friendly, better aesthetically and, most importantly, it was cheaper!

In this section, the environmental impact calculation (EIC) for the UHPdC composite bridge is presented and is compared to that of the original steel beam composite bridge solution. Table III summarises the environmental data used in this comparative study, with details on the derivation of the environmental impact data on the building material provided in Voo and Foster [6]. The table has been prepared to help calculate the equivalent embodied energy (EE), $CO_2$ emissions and global warming potential (GWP) for particular concrete mix designs and materials.

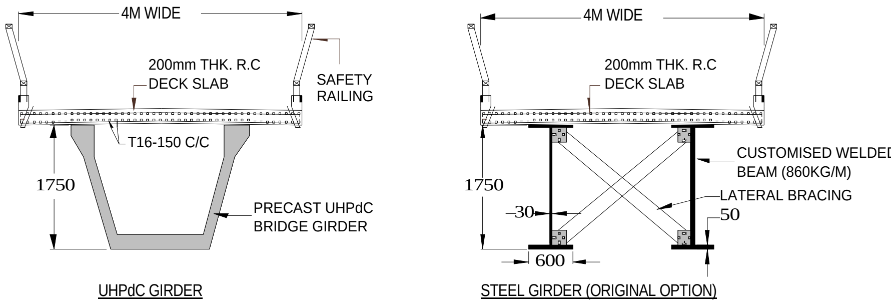



**Fig. 4.** Comparison of UHPdC girder against steel girder composite bridge.

**Table III.** Environmental data.

| | **Units** | **Standard UHPdC (wt. 2% Steel Fiber)** | **Grade-40 (wt. 15% PFA)** | **Steel, Strand, Reo.** |
|---|---|---|---|---|
| **Density** | **kg/m$^3$** | 2400 | 2350 | 7840 |
| **EE** | **GJ/m$^3$** | 7.71 | 1.728 | 185.8 |
| **$CO_2$** | **kg/m$^3$** | 1065 | 297.5 | 17123 |
| **$NO_x$** | **kg/m$^3$** | 4.86 | 1.66 | 55.38 |
| **$CH_4$** | **kg/m$^3$** | 0.76 | 0.12 | 30.65 |
| **GWP** | **kg $CO_2$ eq. /m$^3$** | 2532 | 795 | 34392 |
| **EE** | **MJ/kg** | 3.231 | 0.744 | 23.70 |
| **$CO_2$** | **kg/kg** | 0.446 | 0.128 | 2.184 |
| **$NO_x$** | **g/kg** | 2.035 | 0.714 | 7.064 |
| **$CH_4$** | **g/kg** | 0.318 | 0.052 | 3.909 |
| **GWP** | **kg $CO_2$ eq. /kg** | 1.060 | 0.342 | 4.387 |

In brief, Global Warming Potential (GWP) is a measure of how much a given mass of greenhouse gas is estimated to contribute to global warming over a given time interval. It is a relative scale that compares the gas in question to that of the same mass of $CO_2$. A 100-year of time horizon is most commonly used and it can be expressed as:

$$\text{100-year GWP} = CO_2 + 298\ N_2O + 25\ CH_4 \tag{1}$$

and units of equivalent tonnes of $CO_2$.

In Table IV the material quantities used in the construction of the bridge are summarised (in terms of weight) and the EIC for the two bridge designs determined. In the calculation of the material quantity, only the superstructure is considered herein. The EE, $CO_2$ emissions and 100-year GWP is obtained by multiplying the material volumes by the environmental data given in Table III.

**Table IV**. Material quantities and environmental impact calculation (EIC).

| | | UHPdC (m$^3$) | G40 Concrete (m$^3$) | Strand (tonne) | Reinf. Bar (tonne) | Steel (tonne) | |
|---|---|---|---|---|---|---|---|
| **No.** | **UHPdC Composite Bridge** | | | | | | |
| **1** | **Precast U-girders** | 47.7 | - | 6.66 | 2.34 | - | |
| **2** | **RC deck** | - | 43.38 | - | 8.64 | - | |
| | **Sub-Total** | 47.7 | 43.38 | 6.66 | 10.98 | - | Total |
| **A** | **Mass of material used (tonne)** | 114.48 | 101.9 | 6.66 | 10.98 | - | 234.1 |
| **B** | **Embodied energy (GJ)** | 368.0 | 74.97 | 157.8 | 260.23 | - | 861.0 |
| **C** | **$CO_2$ (tonne)** | 50.80 | 12.91 | 14.55 | 24.0 | - | 102.2 |
| **D** | **GWP (tonne $CO_2$ eq.)** | 120.8 | 34.49 | 29.22 | 48.17 | - | 232.7 |
| **No.** | **Steel Welded Beam Composite Bridge** | | | | | | |
| **1** | **Steel welded beam** | - | - | - | - | 86 | |
| **2** | **Bracing (10% of beam)** | - | - | - | - | 8.6 | |
| **3** | **RC deck** | - | 43.38 | - | 8.64 | - | |
| | **Sub-Total** | - | 43.38 | - | 8.64 | 94.6 | Total |
| **A** | **Mass of material used (tonne)** | - | 101.94 | - | 8.64 | 94.6 | 205.2 |
| **B** | **Embodied energy (GJ)** | - | 74.97 | - | 204.77 | 2242 | 2521.8 |
| **C** | **$CO_2$ (tonne)** | - | 12.91 | - | 18.87 | 206.6 | 238.4 |
| **D** | **GWP (tonne $CO_2$ eq.)** | - | 34.49 | - | 37.90 | 415 | 487.4 |

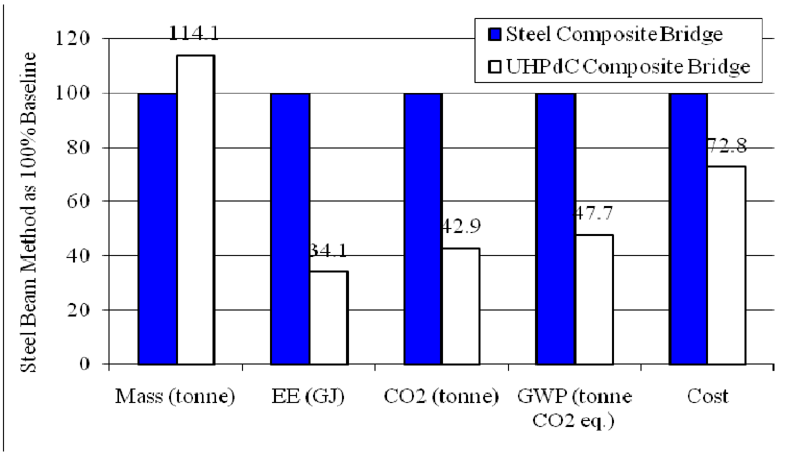



**Fig. 5**. EIC assessment for UHPdC and steel composite bridge design solutions.

A comparison of the EIC results is presented in Fig.5. In terms of material consumption, the UHPdC solution consumed 14% more material (in terms of weight) than the steel-composite girder solution. In terms of environmental impact, however, the UHPdC solution had 66% less embodied energy and 57% less $CO_2$ emissions. In terms of the 100-year GWP, the UHPdC solution gives a reduction of 52% over the steel-composite girder design. In addition to the environmental cost savings, the UHPdC composite bridge superstructure resulted in a projected cost saving of 27%. Thus, the UHPdC solution was not just better for the environment, it was a more economical solution based on initial costs. When maintenance costs are considered, the UHPdC solution is vastly more economical!

## Conclusions

In January 2011, the Malaysia Ministry of Works completed construction of a span 50 m span prestressed motorway bridge that was optimized for a combination of structural performance, durability, sustainability and constructability. The bridge was constructed at a village crossing the Sungai Linggi River. This bridge is the first of its type in Malaysia and currently the world's longest motorway composite bridge made of UHPdC. This paper presented an overview of the construction of the bridge and on a comparison against a conventional steel-composite bridge solution for environmental impact. The UHPdC design was confirmed to be a greener solution as measured by the embodied energy, $CO_2$ emissions and 100-year GWP, which were, respectively, 66%, 57% and 43% less than of the conventional approach. In conclusion, UHPdC technology opens the door for new design approaches and can make concrete structures more cost feasible, sustainable and environmental friendly.

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