Concrete Bridge Design and Construction series

This series is authored by the Concrete Bridge Development Group (CBDG).

The group aims to promote excellence in the design, construction and management of concrete bridges. With a membership that includes owners, designers, academics, contractors and suppliers, it provides a focus for the use of best practice, innovation, training initiatives and research and development. Further information on the CBDG can be found at: www.cbdg.org.uk

No. 9: High performance concretes and new materials

Introduction

Here, we examine the various high performance concretes that might be used for concrete bridges, to make them either quicker and easier to build, or more economic. The advantages of high strength, lightweight, fibre reinforced and self-compacting concretes are described, together with the use of new materials that can replace steel for both reinforcement and prestressing.

The specification for high performance concretes needs to identify the required concrete strength, cover to the reinforcement, cement content, water/cement ratio and cement type – all of which will depend on the particular site and environmental conditions. Working to these specifications will ensure that the concrete is best suited to its location in the bridge, as well as being resistant to carbonation and chloride ingress, in order to provide a long (and low maintenance) working life. The choice of cement and admixture type will also have an impact on the speed of construction, due to the rate of gain of strength; which in turn has an influence on some of the construction methods. Many of these topics are discussed in CBDG TG 5[1].

High strength concretes

High strength concretes (HSCs), typically with higher cement contents and lower water/cement ratios (less than about 0.40) than normal strength concretes (NSCs), can offer many advantages for bridges by allowing the use of shallower, thinner, lighter and more durable sections, where higher compressive and shear stresses can be adopted (Figure 1). It is possible to use longer spans or to have higher load-carrying capacity without increasing member sizes. Higher early strengths will also speed up the construction process and allow the earlier removal of falsework or application of prestressing. The durability of the section is also considerably improved – to the extent that ultra high strength concretes (UHSCs), which are very dense, are virtually impermeable. This results in high resistance to carbonation, chloride ingress and degradation by abrasion. The low permeability of HSC results in lower maintenance costs and a longer service life.

Characteristic cylinder strengths of 40–60MN/m^2 are the norm for prestressed concrete schemes, though strengths of 60–80MN/m^2 are becoming more common for some types of precast decks, mainly through the use of water-reducing admixtures. These higher strength concretes are generally referred to as HSCs. Very high strength concretes (VHSCs) with strengths of 80–150MN/m^2 are achieved through the additional use of a finely graded pozzolanic material, such as silica fume (or microsilica). UHSCs have strengths of 150–225MN/m^2. These concretes are very dense, with high tensile and flexural strengths through the use of silica fume or silica flour and high strength steel fibres (Figure 2). Table 1 provides a summary of these various grades. HSCs are covered by most codes of practice around the world, but VHSCs and UHSCs are not generally described. However, HSCs and VHSCs are becoming more popular, as further research and experience allows the use of thinner sections and higher capacities; particularly by allowing bridge deck webs to become lighter, making significant savings in self-weight loads and prestressing.

Fly ash is used extensively in HSC as the pozzolanic activity in the concrete takes place over a longer period than with Portland cement (CEM1), contributing to higher ultimate compressive strengths. Ground

Table 1: Grades of concrete strength

Concrete grade	Notation	Characteristic strength (MN/m^2)	
		Cylinder	Cube
Normal strength	NSC	40–60	50–75
High strength	HSC	60–80	75–100
Very high strength	VHSC	80–150	100–150
Ultra high strength	UHSC	150–225	150–225

Figure 1
Flintshire Bridge, UK (with 70MPa cube HSC)

granulated blast furnace slag (GGBS) is also used widely for strength, improved durability and reduced heat of hydration effects. The fineness (m^2/kg) of silica fume particles is almost 100 times greater than CEM1 particles and therefore the density and hardness of the cementitious paste is considerably improved, making silica fume well suited to VHSC or UHSC. In all cases, high range water reducers are likely to be used to maintain consistence without increasing the water/cement ratio. Additionally, all the aggregates (typically crushed rock) should be strong and durable. The Concrete Society's technical report on cementitious materials[2] refers to the use of these various components.

All HSCs need good quality control of the production and placing of the concrete, as well as proper curing and testing. As the water/cement ratio of these mixes is lower than NSC, continuous external moisture input is needed over the first seven days after placing the concrete, to avoid self-desiccation i.e. where there is not enough water to fulfil the hydration potential of the cementitious components. Various wet curing methods are possible, including covering the surfaces with wet mats or other absorbent materials.

HSCs show a more brittle behaviour than NSCs and thus, for occasions when enhanced ductility is required, it may be necessary to incorporate additional reinforcement.

HSCs have been used in bridges widely in the US, Canada, France, Scandinavia and Japan, especially over the last 20 years. In all cases, HSCs have been used to enable shallower sections, fewer members, lighter sections (with less prestressing) or more durable bridges with a longer life – particularly in aggressive environments. Cost savings have resulted from both a reduced initial and whole life cost. High strength bridge concretes are covered in CBDG TG 6[3] (with an extensive reference to other documents), while TP 7[4] describes the testing of high strength concrete beams.

Lightweight concretes

Lightweight aggregate concretes (LWCs) have been used widely and successfully in bridge construction for more than 80 years. Decisions to use LWC were generally the result of economic advantages, mainly associated with reductions in the self-weight loads, giving rise to savings in reinforcement and prestressing, as well as in the substructure costs. Although the use of LWC can often bring a competitive advantage to a wide range of bridge types (where the total material savings across the bridge more than offset the increased cost of the lightweight material), the common understanding is that it does not become competitive for bridges until spans reach 100m (Figure 3). LWC can therefore be competitive for these longer spans where the greater effects on the self-weight can reduce the prestressing by significant amounts, i.e. by more than 15%.

LWCs are defined as having an oven dry density of 800–2000kg/m^3, compared to 2000–2600kg/m^3 for NWCs. However, to achieve the required concrete strengths for bridges, only the coarse aggregate component of the mix is made from lightweight aggregates, giving a realistic range of densities of 1600–2000kg/m^3. Further developments in the use of admixtures and materials may also allow bridge concretes to be made using lightweight fines. Lightweight aggregates are made from pelletised GGBS and fly ash, and expanded clay, slate or shale; many of which are known by their trade names, such as Lytag®, Liapor® and Leca®. A substantial portion of LWC in many countries, therefore utilises a waste product (GGBS or fly ash) in a sustainable manner.

Most codes of practice around the world cover these LWCs. In Europe, the range of LWC cylinder strengths that are suitable for bridges range from 35–80MN/m^2 (cubes of 40–90MN/m^2), although typically, the actual range used is more like 35–60MN/m^2 (cubes of 40–65MN/m^2), and in the UK, the current range only extends to 45MN/m^2 (cubes of 50MN/m^2 as in Figure 4). A number of properties of LWC are different to those of NWC. The early thermal behaviour is better due to the lower coefficient of thermal expansion (8 x 10^{-6}/°C) and the higher tensile strain capacity – both of which limit early thermal cracking. For hardened concrete, the general rule is that strength increases with density. Shear and bond characteristics are lower than with NWC and various codes worldwide apply reduction factors of 0.8–0.95. The deformation characteristics of LWC are also different, with elastic modulii being 0.5–0.85 of the equivalent NWC grade – though creep strains are actually very similar and shrinkage strains are about 20–30% higher. Higher prestress losses, which are mainly a result of the lower elastic modulii, should also be considered.

Care should be taken during the concreting, as the much higher porosity of the lightweight aggregates will have a significant impact on the free water content of the concrete, which in turn affects the consistence as well as the final performance. So for good quality control, aggregates should be stored at a consistent saturated moisture state.

Based on the cost of the concrete alone (which might be 30–100% higher), it is difficult to justify the use of LWC, as the aggregates are more expensive and the mix requires a higher cement content to achieve the same equivalent strength. However, the reduced self-weight and falsework loads, the reduction in the prestressing and substructure costs, and the increasing costs of normal aggregates, should all be taken into account for a proper assessment. Typical savings on the whole bridge might be very small or non-existent for short span bridges, but can reach 5–10% for longer spans, especially where spans are over 100m. Bridges containing LWC have been used widely in the US, Canada, Europe, Russia and Japan, especially over the last 50 years, and in all cases LWCs have been shown to be as durable as NWCs, with no difference in maintenance costs. Bridges with LWC are fully described in CBDG TG 8[5], which also has an extensive reference list.

Fibre reinforced concretes

Fibre reinforced concretes (FRCs) are traditional concretes containing a percentage of steel or synthetic/polymeric fibres, whose main purpose is to enhance toughness, ductility, fire resistance, or energy absorption under impact. Micro-synthetic fibres can reduce the formation and development of cracks due to early-age plastic settlement, whereas macro-synthetic and steel fibres can provide a degree of post-cracking, load-carrying capacity, depending on their type, size and dosage, and can thus control crack spacing and width. The *fib* Model Code[6] provides some structural design guidance but generally, few codes cover this aspect, and the Eurocodes will not incorporate such clauses for FRC until 2020. However, the use of FRC in bridges is very limited and is mainly as a supplement to traditional reinforcement, in order to limit cracking or to provide particular impact resistance. Non-participating, permanent formwork panels, made from glass fibre reinforced concrete (GRC), were

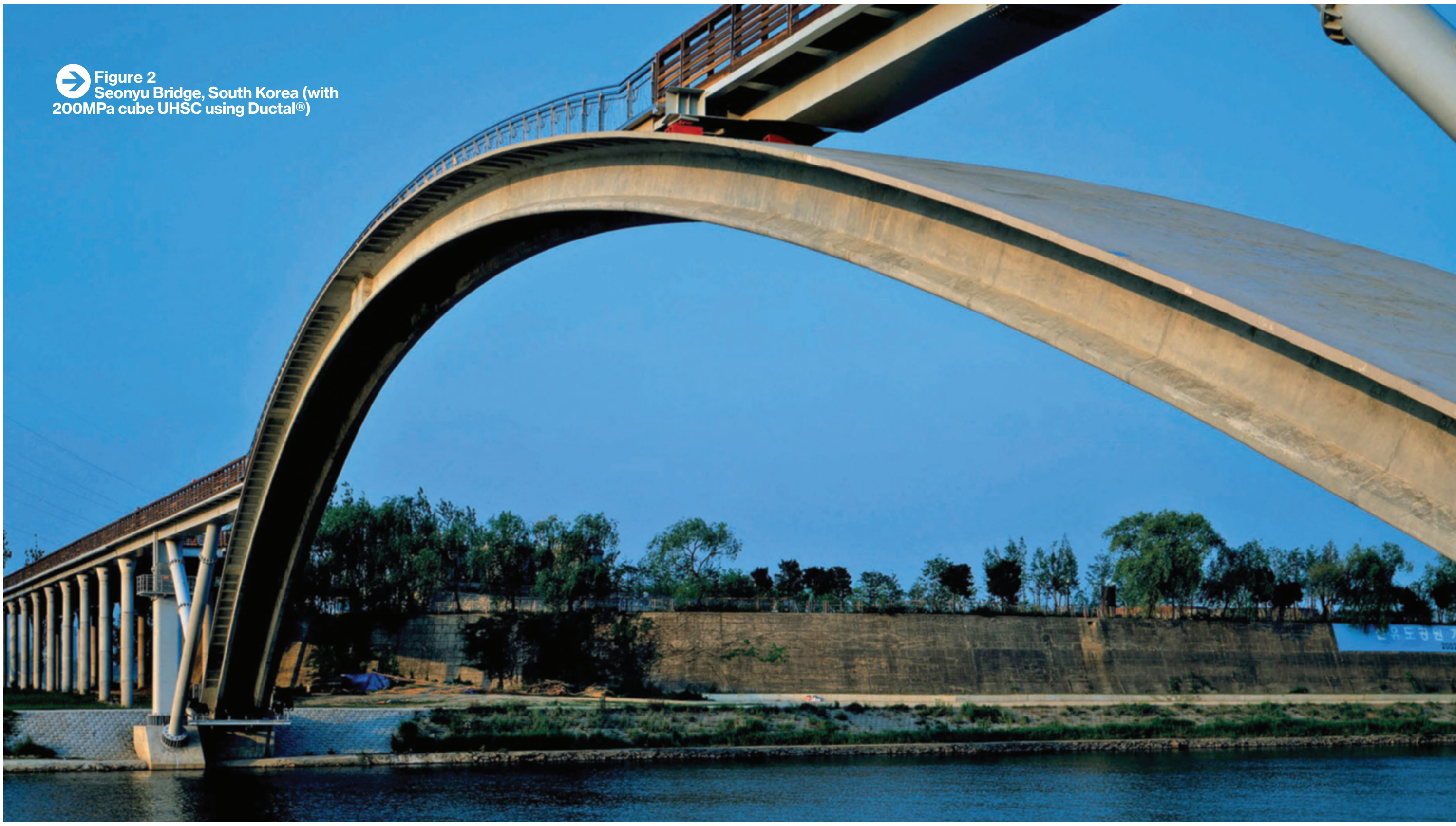

Figure 2
Seonyu Bridge, South Korea (with 200MPa cube UHSC using Ductal®)

Figure 3
Raftsundet Bridge, Norway (298m span with 65MPa cube LWC)

Figure 4
Medway Crossing Viaducts, UK (152m spans with 50MPa cube LWC)

discussed in a previous article in this series[7]. They are widely used as soffit formwork between precast concrete beams (Figure 5). They can be designed with a range of profiles and are usually reinforced with either nylon or polypropylene fibres and glass fibre reinforced polymer bars.

The use of fibre reinforced plastics or polymers (FRPs), where long glass, carbon or aramid fibres are encased within a resin for strengthening purposes, will be covered in a future article in this series, while the use of FRP as a replacement for traditional reinforcement or prestressing, is described in the 'New materials...' section of this article. As with FRC, FRPs will be incorporated into the next generation of the Eurocodes. CBDG TG 3[8] describes the uses of fibre composites in concrete bridges, while CBDG TG 10[9] looks at enhancing the capacity of bridges. CBDG CPS 7[10] examines strengthening measures and The Concrete Society also has two good summary reports[11,12].

Self-compacting concretes

Self-compacting concretes (SCCs) must flow under their own weight and fill the formwork completely, producing a dense and uniform concrete without segregating or the need for compaction. They are not simply high workability concretes, as these still need to be compacted. The properties of the hardened concrete can cover the whole range of required strength and durability. The Japanese first developed SCC more than 25 years ago in order to improve compaction around highly congested reinforcement. The greatest single application to date is at the world's longest span bridge, the Akashi-Kaikyo, which contained around 500 000m^3 of SCC (Figure 6). As the material will flow without segregation from one end of the pour to the other, the need for temporary access and plant is significantly reduced. The rate of placing needs to be controlled to allow the entrapped air to escape, and so may not be faster than normal concrete, but as it is continuous, the completion of the overall concreting operation may be quicker. With the absence of vibrators, the major benefits are quieter worksites and the avoidance of vibration-related injuries.

There is not a particular concrete mix that works in all cases, but to enable self-compaction without segregation, the paste and mortar volumes must be carefully balanced. The cementitious content is typically greater than with normal concrete and can include GGBS or fly ash additions, along with limestone powder, to act as a fine filler. High range water reducers are used to impart fluidity and control water content. Viscosity-modifying admixtures can be added to control segregation but ideally, with the availability of appropriate constituents, this addition should be kept to a minimum – especially if visual concrete is required. As all these fine particles make the microstructure of SCC more dense, the strength and durability of the hardened concrete is generally increased, when compared to traditional concrete that has the same water/cement ratio. The formwork for SCC needs to withstand higher pressures than traditional mixes and, depending on the method of placing, the formwork will probably need to be designed for the full hydrostatic pressure (Figure 7).

All the evidence to date suggests that SCCs have the same long-term properties as traditional concretes of the same strength and water/cement ratio. However, they are generally of a higher quality, with fewer voids and a denser microstructure. SCC may be more expensive than traditional mixes, but this deficit can be offset by the reduced labour requirement. Faster bridge deck construction times are also possible due to the increased workability and ease of flow around reinforcement. The economics of SCC are best displayed when they have been incorporated at the start of the design process, taking full advantage of all the possible material, labour and plant savings. Further national standards and specifications are still being developed and a fuller summary of all these issues can be seen found in CBDG TG 7[13] and in a technical report from The Concrete Society[14].

New materials for reinforcement and prestressing

Extensive measures are now taken with concrete specifications to identify the required concrete strength, cover, cement content, water/cement ratio and cement type – which

Figure 5a
FRC formwork panel with glass fibre bars

Figure 5b
FRC formwork panels in position

Figure 6
Bridge anchorages with SCC: Akashi-Kaikyo Bridge, Japan

Figure 7
Pier replacement with SCC: Whitecleave Viaduct, UK

Figure 8
FRP reinforcing bars with glass fibres

ensure that the embedded steel is protected for the whole life of the bridge. In the most extreme conditions, it might also be necessary to use stainless steel reinforcement, although at present, no stainless steel has high enough strength to replace prestressing cables. Stainless steel is 2–4 times the cost of normal steel and is therefore rarely justified. It is also not covered by most codes of practice, although it will be added to the next generation of Eurocodes. Equally, the more widespread use of FRP as a replacement for steel is currently impractical. As such, materials remain very expensive. Although the rapid expansion of FRP in the aerospace, marine and automotive industries will continue to develop these products, prices for the civil engineering industry will only fall with innovation on a commercial scale.

The three main fibres used in FRP are glass, carbon and aramid, all of which have very high ultimate tensile strengths (UTS) of 3000–5000MN/m^2 and low weights. Aramids are manufactured fibres consisting of aromatic polyamides, one of which is better known by its trade name, Kevlar®. Carbon fibres have a similar elastic modulus to steel, whereas glass fibres are less than half that of steel, and aramid fibres are somewhere in between. They all exhibit linear elastic responses up to ultimate load, with no significant yielding. In most cases, the only permitted resins, within which the fibres are generally bound to form a composite, are epoxy or vinylester, as other types of resin might be prone to chemical attack by the alkaline concrete.

Composite bars are generally made with either glass or carbon fibres, where about 2/3 of the composite consists of fibres. The properties are correspondingly lower than those of the raw fibres. The UTS of glass fibre polymer bars (Figure 8) is around 1200MN/m^2, rising to about 2000MN/m^2 for carbon fibre. The elastic modulii are around 40 000MN/m^2 and 150 000MN/m^2, respectively. Carbon fibre bars therefore, have similar properties to steel prestressing strand. However, the higher working strains in such sections will make them uneconomical or unserviceable for normal conditions, in the same way that steel strand cannot be used as passive reinforcement. These FRPs are also prone to stress rupture (whereby a material with a high permanent load will creep to failure) although the strength for occasional short-term loads remains virtually unchanged. Various manufacturers in the US, Canada, Europe and Japan make these polymer bars, generally by a pultrusion process, which is often augmented by a second stage to improve the bond characteristics of the surface (though this treatment is rarely needed). Most available systems only offer straight bars but the development of methods that utilise the flexibility of the fibres, such as with textile or mesh reinforcement, may be the best way to form bends. The first, very simple, concrete bridge in the UK to use FRP bars was built in 1995, followed by a number of others worldwide in the 20 or so intervening years.

Prestressing cables and cable-stays are generally made with either carbon or aramid fibres. Most manufacturers produce FRP cables from a pultrusion process with resins, though the Parafil® system uses aramid/Kevlar® fibres and is resin-free. The strain problems with reinforcing bars (noted previously) are eliminated once the cables are prestressed, although these cables are also prone to stress rupture, which reduces the working stresses to about 65% of the short-term strength, which is about 1200MN/m^2. Most cables have their anchors fitted in the factory, using adhesives inside

Figure 9
Aberfeldy Bridge, UK: FRP Parafil® cable-stays

stainless steel barrels, although some manufacturers have developed wedge systems similar to steel cables. Stress concentrations within the anchors are still an issue for carbon fibre cables, where the anchorage will always fail before the cable. However, aramid fibres are much more robust and anchorages exist that are stronger than the cable. Pre-tensioned solutions should use internal, bonded cables using resins, whereas post-tensioning should use unbonded resin-free cables, which could be internal or external. Around 50 concrete bridges have been built worldwide over the last 20 years using FRP prestressing cables or cable-stays, many of which have been monitored for research (Figure 9).

The benefits of all these FRP bars and cables are increased durability, high strength and light weight; making them well suited to both new and strengthening works. Even though their capital cost is still much greater than that of steel, the whole life cost may become competitive. Yet the use of FRP bars as a replacement for steel reinforcement will only ever be practical in very aggressive environments with relatively light loads. Nevertheless, the use of FRP cables as a replacement for prestressing is likely to be a real step forward for all concrete bridges, subject to there being significant investment and innovation on a commercial scale in our industry. To take best advantage of these cables, designers need to incorporate the use of composites at the beginning of the design process, as it will change the whole section layout and the way in which compressions and shears are also carried. Some design guidance exists in Japanese, Canadian and American codes and further design guidance will appear in the Eurocodes from 2020. CBDG TG 3[8] describes the development in the uses of FRP, while Dr Chris Burgoyne also gives an excellent summary[15].

Conclusions

High strength, lightweight, fibre reinforced and self-compacting concretes have a significant and wide range of uses in various types of concrete bridge; from simple slab and beam structures, through to the cable-stayed bridges that will be covered in a future article in this series. Though FRPs are not currently widely used in concrete bridges due to their cost, this circumstance may change over time. At the point such materials become competitive and therefore advantageous for bridgeworks, the increasing interest in carbon or aramid fibres as a replacement for prestressing steel will be fully realised.

References and further reading

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