UHPC in the UK

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Abstract:

Despite a recent high-profile application at Hammersmith Flyover, adoption of Ultra High Performance Concrete (UHPC) in the UK remains limited. This contrasts with use globally which continues to grow. A state of the art study was undertaken on behalf of Highways England, the government-owned company responsible for operating and maintaining the UK's Strategic Road Network, with objectives to identify possible applications and benefits of UHPC, barriers to use, and recommendations to promote increased use on Highways England's infrastructure. Applications for new-build (full components, in-situ connections) and structural enhancement (link slabs, deck overlays, column jacketing) were identified. Highways England owns a wide range of transport infrastructure, including 6800+ concrete bridges, the majority of which are over 40 years old. This makes structural rehabilitation an important topic, and provides justification for promoting implementation of UHPC. The absence of UK standards and guidance for design and execution of UHPC is a key barrier to widespread adoption; some other European countries making use of UHPC have some form of published literature. Further issues include lack of experience amongst designers and contractors, limited numbers of UHPC suppliers, and the absence of knowledge and precedent regarding technical approval. Recommendations are made for stimulating use of UHPC in the short term and include preparation of an action plan identifying additional sources of funding (e.g. innovation funds), conducting a whole life cost benefits analysis, and developing a clear approvals process for UHPC. To pave the way for widespread implementation in the longer term, recommendations include sponsorship of pilot projects, engagement with the academic community, and promotion amongst designers and sub-contractors.

Keywords:

International Experiences, Bridges, Design Criteria, Material Specifications, Project Examples / Applications, Project Specifications and Special Provisions, International Specifications

1 Introduction

The profile of ultra-high performance concrete (UHPC) was raised in the UK infrastructure sector when it was used as part of the Hammersmith Flyover remedial works (Cousin 2017; Jackson 2017). Its high strength allowed it to be cast into compact anchor blocks which were attached to the side of the structure and used to facilitate the addition of a new external post-tensioning system. However, this example appears to be an anomaly, since other reported civil applications have been limited. UHPC has been used in some high profile architectural applications, for example, the new staircase for Somerset House, a large Georgian neoclassical building in Central London (Fabbri 2017), but again these amount to only a handful of uses. Despite offering potentially attractive properties, and its use growing worldwide, so far UHPC has not been widely used in the UK.

2 Background

This study originated from a presentation given by Dr Voo Yen Lei to the UK Bridges Owners' Forum about his company, DURA, and the work they have carried out in Malaysia constructing bridge decks from pre-cast UHPC, with a portfolio of 93 completed structures as of 2017 (Voo 2017). The Bridge Owners' Forum is a UK based task group with aims of promoting collaboration amongst bridge owners and identifying research needs to assist best practice in design, construction, and management of bridge infrastructure. Voo outlined the many benefits of UHPC, and showed that rolling it out on a larger scale was attainable.

The talk highlighted the scarcity of efforts in the UK to champion UHPC. Based on the interest it generated, Highways England, the government-owned company responsible for operating and maintaining England's Strategic Road Network, and a member of the Bridge Owners' Forum, commissioned WSP to prepare a state of the art report on UHPC. The investigation and promotion of innovative materials and techniques is a key ambition for Highways England, as outlined in its 2015-2020 procurement plan (Highways England 2019). This ambition is underpinned by two important topics. First, assuring a high level of construction quality to ensure that structures are built efficiently, safely, and to last. Second, the need to undertake the necessary maintenance and rehabilitation to ensure the structural health of their asset stock going forward. Intrusive measures to repair structures can be amongst the greatest engineering challenges and can provide an incentive for the use of novel materials and methods.

There are also signs that other organizations in the UK are starting to examine UHPC and the opportunities it brings. Highways England is in discussions with HS2 (organization delivering a new UK High Speed railway line from London to Birmingham), that is also investigating use of UHPC in its projects. TfL (Transport for London) used UHPC in its strengthening work on Hammersmith Flyover. Table 1 presents selected examples of recent use of UHPC in the UK.

Table 1. Selected examples of recent use of UHPC in the UK

Structure	Principal Contractor	Owner	Year	Description
Somerset House Miles Stair	Coniston Ltd	Somerset House Trust	2013	Cantilevered precast stair treads for 26m high circular staircase in Grade I listed Georgian building. (Fabbri 2017)
Hammersmith Flyover	Costain	TfL	2015	UHPC post-tensioning anchor blocks fitted to existing concrete structure. (Cousin 2017; Jackson 2017)

Gatwick Airport	Kier	Gatwick Airport Ltd.	2017	Pre-cast UHPC used to strengthen stairs and ramps. (Freyssinet 2017)
Arndale Shopping Centre	Kier	Performance Retail Partnership / Legal & General	2018	Pre-cast UHPC used to strengthen columns. (Freyssinet 2018)

3 Literature Review

3.1 Comparison vs. Traditional Concrete

A broad range of sources was considered, including national and international design codes, standards and specifications, conference proceedings, articles, presentations, reports, and technical notes. Initial efforts identified definitions and distinguishing features of UHPC and how it differed from traditional concrete across a range of criteria. Differences include for workability and rheology, ductility and toughness, characteristic strength, curing time, stiffness, creep and shrinkage behavior, fatigue behavior, durability / permeability, and fire resistance. These are discussed in detail by Russell 2012, Fehling 2014, and Abbas 2016. Economy for UHPC was compared qualitatively against traditional concrete, considering factors such as ease of design, volume of concrete required, level of reinforcement required, cost of formwork, ease of pre-casting, ease of transport, ease of site assembly, ease of in-situ pours, and ease of maintenance. UHPC was identified as having properties that set it apart from conventional engineering materials, opening the possibility for innovative applications. It was also identified as having a variety of barriers to use, including lack of UK guidance and high cost.

3.2 UK Guidance

This study placed particular interest in highway applications, given the interest of the funding body Highways England. In the UK, highway works are designed and specified using the Design Manual for Roads and Bridges (DMRB) and the Manual of Contract Documents for Highway Works (MCHW). The DMRB is a fifteen-volume collection of standards, guidance and other documents relating to the design, assessment and operation of trunk roads, including motorways. The MCHW is a six-volume series which includes the *Specification for Highway Works*. Other major asset owners such as Network Rail (owner and infrastructure manager for most of the railway network in the UK) have their own forms of guidance. The literature review confirmed the absence of UK UHPC guidance for design, specification, execution, or acceptance, either in the DMRB or in other sources.

Standards applicable under the DMRB include the following: for design, Eurocode (EN 1990 and EN 1992); for execution, EN 13670; for specification, performance, production and conformity of concrete, EN 206 and BS 8500; and for pre-cast concrete products, EN 13369 (Highways England 2016). It was identified that EN 1992 is not suited to designing UHPC. The limit for concrete compressive strength in EN 1992 is 90MPa (13.0ksi). UHPC is commonly defined as being greater than 150MPa (21.7ksi). Furthermore, there are many differences between the approaches adopted for concrete and for UHPC stemming from UHPC's special structural properties, for example its ability to withstand sustained tensile stress, typically >5MPa (0.72ksi) at ultimate limit state. The rules provided under EN 1992 for managing the stress-strain relationship, creep and shrinkage, cover, and crack width all require revision for UHPC (BFT Intl. 2019).

3.3 International Guidance and Applications

Other countries have developed approaches which allow UHPC to be used, but challenges remain. France has been a leader in producing guidance, publishing codes for design and specification in 2016 (Setra 2016[a], 2016[b]), and one for execution in 2018 (Setra 2018). Switzerland has produced a code for design and execution (SIA 2016), and Spain and Germany are preparing guidance (Schmidt 2017; López 2017). Task Group 4.2 of fib is devoted to the study of UHPC and is developing guidance although it is not yet available (fib 2019). The French code adopts a structure aligned to EN 1992 but for many of the clauses it states: 'Does not apply', including for Eurocode principles (marked with a "P") which are generally mandatory. Instead of specifying constituent products, it specifies performance requirements (an 'Identity Card'). France has used UHPC for new-build and rehabilitation works. New build has seen construction of slender, elegant structures, making use of its high strength, e.g. La République Bridge (Ricciotti 2017), but has also been used in 'ordinary' applications, e.g. as filler beams for Pinel Bridge (Thibaux 2008). In Switzerland there have been 50+ examples of rehabilitating structures such as bridge decks by adding an overlay of UHPC (Brühwiler 2016). The process involves stripping the concrete cover and adding a layer of reinforced UHPC. The UHPC has a sufficiently strong bond to achieve composite action with the existing deck and increase its capacity. The surface is also highly durable, preventing ingress of water and chlorides.

The USA has developed guidance for UHPC. Authorities and industry bodies in the USA have tended to focus efforts on producing guidance for specific applications. For example, the Federal Highway Administration (FHWA) has produced a guide for 'Design and Construction of Field-Cast UHPC Connections' (Graybeal 2014) and the American Society for Testing and Materials (ASTM) has produced the standards 'ASTM C1856 / C1856M – 17, Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete' (ASTM 2017). The FHWA's efforts developing guidance for UHPC fit into their broader drive for Accelerated Bridge Construction (FHWA 2019; Nault 2017). The potential for such techniques to be applied to UK infrastructure is considered by Murphy (Murphy 2018). Another North American application has been retrofitting UHPC link slabs to bridge decks (Doiron 2017[b]; Scarlata 2017). Expansion joints in bridges can be a maintenance liability. Link slabs are a good way of eliminating this issue, but ordinarily are invasive to install. Canada is developing guidance for UHPC (Perry 2017). There, column jacketing of bridge piers using UHPC has been carried out (Doiron 2017[a]). This holds promise as an application as it thins down the amount of cover required and is extremely durable.

The achievements of DURA in Malaysia are outlined by Voo 2011, 2016, 2017. More activities are taking place in other countries in Asia too. Japan was the first country to issue guidelines on the use of UHPC (Uchida 2005, Yokata 2007), and continues to be engaged with use of the material. The Peace Bridge in Korea meanwhile was one of the first to be fully constructed from UHPC (VSL Korea 2012). Considerable research is on-going in China where at least five full bridge structures in UHPC have been constructed (Chen 2016, Wang 2016).

4 Potential UK Applications

4.1 New Build

Connection of pre-fabricated elements (pre-cast concrete beams, steel girders etc.) via an in-situ concrete stitch is common practice in the UK. The success of using in-situ UHPC for connections in the USA demonstrates this is a viable alternative to normal reinforced concrete, with the benefit that UHPC connections are smaller, requiring only short lapped bars (Vitek 2016; Graybeal 2014).

Ordinarily for pre-cast concrete beams, hooped bars are cast in, and then longitudinal bars are threaded through the overlapping bars on site. Using UHPC could allow this detail to be reduced to short overlapping straight bars, saving time and materials on site and offering potential health and safety, financial, and program benefits. The benefits of off-site manufacture, and government actions to promote it, are outlined in a UK governmental review (House of Lords 2018).

Pre-cast UHPC elements could include beams for a bridge, segments for a retaining wall, or standardized components such as parapets (Charron, 2013). A key benefit is the associated reduction in section size (Russell 2013, Voo 2012) generating advantages such as reduced transport and cranage costs and reduced carbon footprint. The shallow depths that can be achieved with bridge beams offer potential in terms of providing reduced construction depth and hence increased headroom over existing highway or railways structures when replacing existing decks (Thibaux, 2008). Shear reinforcement may not be required, leading to cost savings in steel and simplifying fabrication (Binard 2017; Voo 2010). The components can also be lighter, reducing requirements for foundation size.

4.2 Structural Enhancement

As of 2016, Highways England owns approximately 6800 concrete bridges, of which a majority are over 40 years old. This makes structural rehabilitation an important theme and creates a market for innovative concrete repair strategies, such as with UHPC. Applicable measures could include: general repairs; column / pier jacketing; deck overlays; link slabs; and strengthening incorporating pre-cast UHPC components.

Traditional reinforced concrete repair and strengthening requires break-out of the structural concrete behind the outer layer of reinforcement. This is time consuming and expensive. UHPC can be cast against the existing concrete because of the strength of its bond. Assuming the concrete is only defective in the cover zone, only this depth needs to be removed. The extent of propping may be reduced or eliminated. This has potential to save time and cost on site and reduce disruption to road users. Reducing labor hours also offers associated health and safety benefits by reducing worker exposure time to hazards. UHPC reduces the volume of concrete required which can be important where space is restricted. Deck overlays are similarly non-invasive. Breakout of the concrete underneath the existing reinforcement is not necessary, bringing the associated benefits. The UHPC acts compositely to strengthen the deck, and provides a highly durable finish.

By utilizing its high strength to reduce section size and levels of reinforcement, relatively small components (e.g. post-tensioning anchor blocks) can be manufactured in UHPC, when compared to traditional concrete equivalents. This opens opportunities for retrofitting elements to existing structures where space is constrained, as was successfully done on Hammersmith Flyover (Cousin 2017, Jackson 2017). Secondary structural elements in existing structures like jack arches or traditional reinforced concrete slabs have been successfully replaced with new, lighter, pre-cast UHPC deck panels (Jafrello 2017, McDonagh 2016) which have the benefit of reducing the loading on the primary structural members and foundations.

5 Barriers and risks to use in the UK

5.1 Design and specification

There is an absence of published guidance in the UK for the design and specification of UHPC. Because UHPC is outside the scope of Eurocode, the approval process becomes more complicated and time-consuming. As defined by BD 100/16, UHPC is an ‘aspect not covered by standards’. Its design requires a '*Departure from Standard*', a document used by the approving authority to certify proposals outside of current standards and hence control the level of technical risk. A Departure from Standard for UHPC would be lengthy, requiring separate justification for design and specification (outside Eurocode, DMRB, and MCHW), and likely stipulate testing. Departing from Eurocode guidance is discouraged in the UK (Highways England 2016).

There is an opportunity to use and adapt the French guidance, given that it is used within the same Eurocode framework. However, there are crucial differences between EN 1992 and French Guidance that would have to be resolved to allow them to be used in the UK. These differences were studied as part of our work for Highways England, and are summarized as follows. Firstly, Nationally Determined Parameters (NDPs) for EN 1992 are generally specified in the National Annex to EN 1992 (BSI 2015[b]). Because the French codes have been drafted for use in France they have the French NDPs implicitly included. For example, α_{cc} is a coefficient applied to the compressive strength of the concrete which is defined in EN 1992. The coefficient takes account of the long-term effects on the compressive strength and of unfavorable effects resulting from the way the load is applied. For traditional concrete in the UK, α_{cc} is taken as 0.85. In France α_{cc} is taken as 1.0 for traditional concrete, and 0.85 for UHPC. Taking α_{cc} for UHPC as 0.85 may be non-conservative when applied alongside UK practice and considering the UK value for traditional concrete. UK concrete codes require shear testing of concretes above 50MPa (7.2ksi) compressive strength. No such provisions are currently required by French UHPC codes.

5.2 Execution and acceptance

There are inherent challenges associated with UHPC's installation. Care must be taken not to pour the concrete over great distances. This can cause the steel fibers to become aligned. Randomness in orientation is essential in ensuring maximum capacity. This requirement can have implications on design program and cost because sometimes scale tests are necessary to ensure a heterogeneous orientation of fibers is achieved. Because it cures so quickly it has a propensity to form a thick crust on its surface known as an 'elephant skin' (Wetzel 2013), and must be poured very soon after mixing, approx. 30mins (Russell 2013). This means generally it either must be pre-cast or mixed in a batch plant on site. A batch plant takes up space and requires the unmixed materials to be stored on site, requiring changes to the way the work is planned. Different tests (e.g. 3-point bending tests) are required for UHPC vs. traditional concrete, complicating the acceptance process since such tests are not necessarily widely available or required for traditional concrete.

5.3 Supply and economy

The high cost of UHPC vs. traditional concrete is well established (Meng 2016; Graybeal 2013; Russell 2013) and is a barrier to wider adoption. Partly this is due to the specialist components of the mix (fine aggregates, high binder and plasticizer content, steel fibers) but there may be other factors that contribute. Non-proprietary mixes, which might offer a cheaper alternative are currently not available, owing to the lack of guidance in this area (El-Tawil 2018).

There are limited numbers of suppliers, contractors, and pre-casters working with UHPC in the UK market and only three types of UHPC are available (Ductal© / BSI© / BCV©). The former, by LafargeHolcim, is the dominant force. The most prolific contractor appears to have been Freyssinet (occasionally Walo) and the pre-caster Thorp. The small number of players is a symptom of lack of demand in the UK market. High costs are likely best attributed to the difficulty for suppliers to achieve economies of scale, as opposed to the inherent lack of suppliers.

5.4 Capability, experience, and perceptions

Many designers will be unfamiliar with UHPC and those that are, may be averse to using it. It takes time and financial investment to develop experience in a new field, so many - whether on an individual or company-wide basis - will prefer to stick with familiar techniques. There is a lack of long-term performance evidence, since the material has only been in use for approximately 20 years. This makes persuading asset owners to use the material more difficult, again for whom it may be ‘safer’ to stick to the established, tried and tested, designs. Part of the reason for UHPC’s success in France and Malaysia has been the willingness of public organizations to work with the private sector to develop innovative solutions to problems, perhaps something less common in the UK. Designers may not consider UHPC because they may think it is too expensive based on its high cost per unit weight. However, the cost ought to be considered in the context of the potential material savings and improvements to whole life cost through reduced maintenance.

6 Promotion of UHPC in the UK

6.1 General

Based on our review, there are instances where UK asset owners could derive tangible benefits via use of UHPC. The USA is realizing the benefits of UHPC now, but this has been preceded by research and investment carried out by the FHWA dating back to 2001. Germany is another country where research grants have stimulated interest in UHPC - the German Research Foundation invested €12M in 34 projects across 20 institutions between 2005 and 2013 (Schmidt 2012). For asset owners in the UK, the first step towards encouraging use should be to develop an action plan, including a business case and communications plan, a program of activities, and budget required to deliver short-, medium-, and long- term actions. To support the business case that would form part of the action plan, asset owners would need to undertake further work to evaluate commercial opportunities and risks, for example, an in-depth comparison of Whole Life Cost for UHPC vs reinforced concrete vs steel. This could involve liaison between asset owners, such as (in the UK) Highways England, Network Rail, and HS2, and other stakeholders to gauge their appetite for collaboration and the sharing of costs and spreading of risks Asset owners could investigate funding sources, e.g. Innovate UK or Highways England innovation fund.

6.2 Design and specification

Enabling design and specification of UHPC in the UK in the short-, medium-, and long-term will require appropriate guidance to be made available. Initially this could be for individual bodies, such as Highways England, who would need to consider the appropriateness of international literature for use in the UK, and what further steps would be required to ensure disparities with UK best practice are resolved (decisions on design factors, testing etc.). In the medium-term this could be developed into an industry-wide publication with contributions from steering groups comprising asset owners and industry experts. Such reports on separate topics have previously been issued by the UK based organization CIRIA (Construction Industry Research and Information Association). Comparably, another innovative material, FRP (fiber-reinforced plastic), has gradually been adopted in civil engineering construction in the UK. CIRIA C779 (2018) ‘Fibre-reinforced bridges – guidance for designers’, resulted from extensive research and was sponsored by Highways England and Network Rail. Although a full specification for FRP has yet to be developed, the guide provides extensive advice to designers. Today several companies are offering pre-fabricated FRP footbridges, which suggests that the public investment has helped stimulate the market. A similar investment in UHPC could also result in a positive outcome.

Longer-term, asset owners could engage with the BSI (British Standards Institution) to determine their appetite for developing a UK-specific Code of Practice, such as a PAS (Publicly Available Specification) by the BSI. PAS documents are fast-tracked guidelines developed by sponsoring organizations to meet immediate market needs. Asset owners could help to identify what further actions would be required, such as conducting appropriate research. Once further codes are issued, e.g. from Germany and Canada (Perry 2017; Schmidt 2017), it may be easier for UK code developers to adopt and enhance those aspects which are most appropriate for UK best practice. Ultimately, there could be moves to develop international standards for UHPC, either by inclusion in the Eurocodes or as an ISO (International Organization for Standardization) standard. There may be opportunities to develop international technical reports as an interim step. National practice and national guidelines could be helpful steps in contributing to such longer-term work.

6.3 Execution and acceptance

Asset owners such as Highways England could sponsor pilot projects to promote the use of UHPC. Initial steps would identify potential projects that would help to develop standards and guidance. To begin with these could be shadow designs carried out by a consultant on behalf of the client. Shadow designs would help to determine the feasibility for using UHPC in different situations and to identify the likely costs for implementing a solution. To reduce and manage risk, the projects themselves could be small, with subsequent projects at an increased size and complexity. Initial pilot projects could involve non-safety critical elements, for example non-structural concrete repairs. Such pilot projects would test three important parts of the process: approval, procurement and execution. Further projects could progress to safety critical elements such as in-situ connections (e.g. between pre-cast beams), and ultimately full structures constructed from UHPC. Evaluation of pilot projects would aid future design development and allow Whole Life Cost comparisons to be made vs. other solutions, refining the business case for use. Pilot projects would raise awareness, improve familiarity and competency in the construction workforce, and identify training needs. In the long-term, these projects could be monitored and evaluated to measure performance and track benefits realization. The outcomes of the monitoring and evaluation would feed back into the development and improvement of the standards and guidance. To enable pilot projects, asset owners would need to work together with the supply chain to identify suitable options and gauge their appetite for sponsoring projects.

6.4 Supply and economy

Expanding on the potential for pilot projects, asset owners could encourage their suppliers to consider UHPC and look at its potential benefits on schemes under their responsibility. It would be beneficial to engage with all members of the supply chain to ascertain their views on UHPC, their needs and concerns, and their appetite to make use of it in the future. Many UK suppliers also have a presence overseas so may have a view based on their international experiences. Asset owners would need to determine how use of UHPC fits into their own procurement strategy. Such work could include research into the supply chain to determine the number of suppliers and degree of competition. Engaging with their counterparts in other countries to discuss their approach to procurement would also be of benefit to asset owners. Going forward, asset owners could work with the supply chain to develop a supporting network for supply and manufacture of UHPC materials and components. Furthermore, asset owners could encourage designers or contractors to look for uses of UHPC on their projects via active engagement during the design development stage or incentivization of innovative applications during tender evaluation.

6.5 Capability, experience, and perceptions

Asset owners interested in promoting the material could organize events to boost awareness, such as webinars, lectures, or conferences, and leverage their industry contacts to invite experts in the field to share their knowledge, boosting UHPC's profile in the UK.

Asset owners could sponsor future research with academic and industry institutions to explore the use of UHPC to raise its profile in the UK. This could also feed into supporting Departures from Standard and development of UK specific literature. To date, we have identified that Liverpool, Cardiff, Portsmouth, and Queens Belfast Universities have all engaged in some form of UHPC related research. Asset owners could commission relevant subject research, for example sponsoring post-graduate research. This would promote the material in the academic sphere, boost its profile in the UK and could usefully feed into the development of Highways England's approvals process for the material.

7 Conclusions

We undertook a state-of-the-art review of the use of UHPC in the UK on behalf of Highways England. Our key findings were:

- UHPC has properties that set it apart from conventional engineering materials, opening the possibility for innovative applications.
- In Europe, North America, and Asia, the benefits of UHPC are already being realized, with guidance in these countries at differing levels of maturity.
- There are many potential applications in the UK, for both new build (e.g. full components, in-situ connections) and structural rehabilitation (e.g. link slabs, deck overlays, column jacketing).
- Interest in UHPC in the UK is growing among asset owners, including Highways England, HS2, and TfL.
- Significant challenges remain to its use in the UK, ranging from issues associated with design; specification; approval; execution; supply; and capability, experience, and perceptions.
- By drawing on international experiences, there are actions UK asset owners can take to enable UHPC's benefits to be realized. Initially this would involve developing their own guidelines, and later contributing to industry-wide guidance. Similar initiatives for other materials such as FRP have proved successful in the UK.
- Asset owners should go further and actively encourage the use of UHPC on their network for appropriate applications. There are many ways they can do this, ranging from promoting it throughout their supply chain, to engaging with the academic community, to sponsoring pilot projects.

It should be noted the views expressed in the report are on behalf of the authors, not Highways England.

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