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Roller Compacted Concrete - Background to the Development of Highways England's Design Guidance and Specification

Highways England Specialist Professional and Technical Services (SPaTS)

Framework Lot 1, Work Package Ref: 1-087, Sub-Task 4 – Ad Hoc Support

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1. Introduction

This report provides an overview the technical innovation associated with the introduction of Roller Compacted Concrete (RCC) into the Design Manual for Roads and Bridges (DMRB) and Manual of Contract Documents for Highways Works (MCWH) Series 1000, Volumes 1 and 2. This innovation includes development of pavement design, material and construction solutions.

Highways England (herein referred to as “the client”) commissioned this work as part of the Highways England Specialist Professional and Technical Services (SPaTS) Framework Lot 1, Work Package Ref: 1-087, Sub-Task 4 – Ad Hoc Support.

The report details progression from a Technology Readiness Level of being used in operational environments which mainly comprised heavy duty pavements and overseas applications on major roads, through to road trials on Highways England’s network and also work with industry to develop the required revisions for the DMRB and MCHW.

The report is structured as follows:

Section 2: Background

Section 3: Features and properties of RCC

Section 4: Mix design and production of RCC

Section 5: Design considerations

Section 6: Production and installation

Section 7: Performance and maintenance

Risks and mitigations associated with the design and construction of RCC have been highlighted throughout this report, building on both international and UK experience with the highway sector and also from the wider pavement construction industry.

Industry liaison on development of the DMRB and MCHW was done in conjunction with Highways England and Britpave. The network trials of asphalt surfaced RCC pavements have been monitored by AECOM as part of the introduction of RCC. These are located on the Elveden Bypass, constructed as part of the A11 Fiveways to Thetford Improvement. The relevant RCC network trial sections works were undertaken by Balfour Beatty and their supplier Tarmac in 2013. Acknowledgements are included at the back of this report.

The primary driver for the adoption of asphalt surfaced RCC onto Highways England’s network is the potential for scheme specific efficiency benefits. These are linked to construction programme and also construction costs versus other pre-existing options in the DMRB and MCHW. A review of the potential efficiency benefits is not included within the scope of this report.

2. Background development and applications

This section gives an outline of the early development and application of RCC. It then goes on to describe RCC's applications around the world and the level of the technology in the UK.

2.1 RCC origin and applications

RCC derives its name from the construction method; it is laid with a paver and compacted by rollers. It is only a concrete in the sense that its main constituents are aggregate, water and cement. It does not behave in the same way as conventional concrete in terms of construction or performance. It does not require reinforcing, dowel bars or formwork for construction. RCC is constructed in a similar fashion to paved Cement Bound Granular Mixtures (CBGM), while having an in-service performance similar to a rigid concrete pavement (Pittman, 1994).

Further details on features and properties of RCC are given in Section 3 of this report.

RCC applications can be traced back to the 1930's and 1940's but these early applications were sporadic and inconsistent. The beginning of RCC in a form that would be recognisable today is with the Canadian logging industry in the 1970's (Britpave, 2013). The industry needed a material that was easy to construct, non-frost susceptible and very hard wearing (PCA, 1999). RCC offered a robust and an economic solution to this challenge.

2.2 Development of the technology

Further development of the RCC was primarily taken forward by the US Army Corp of Engineers who conducted research and development in the 1980's. This research was developed further in the 1990's so that RCC could be used for ports and container handling facilities. The use of RCC for these applications has increased in the intervening years; including HGV parking, hardstanding areas and interstate hardshoulders (Britpave, 2013).

The technology has moved from being mainly associated with North America to other parts of the world. Australia and New Zealand have published guides and specifications for the use of RCC in highway and industrial pavements (Cement and Concrete Association of New Zealand, 1993).

In the 1990's Spain started research and development works with it on their road network. They used RCC in conjunction with asphalt surfacing. A great deal of work was done to mitigate the risk of reflective cracking in the asphalt surfacing; including crack control systems and iterations of crack spacing.

Transverse natural crack spacing's of 15 m or greater were found depending on the RCC properties and layer thickness. A simplified explanation of this is that drying shrinkage produces the large natural crack spacing's (Williams, 1986). Drying shrinkage is higher for higher water content mixes such are typical for concrete, while RCC is designed with a relatively low water demand to suit roller compaction. Therefore, as a generalisation, the relatively low water content of RCC versus typical concrete, results in reduced potential for shrinkage and a relatively widely spaced natural crack pattern. These natural cracks tend to be relatively open and irregular resulting in a high risk of early life reflective cracking occurring through any overlying asphalt pavement. It is important to note that these reflective cracks are not a structural failure of the pavement, but if left unsealed they can potentially result in water penetration into the pavement and can result in secondary defects.

This consideration is common to all pavement types from cracked lower layers in asphalt pavements, through to composite and rigid pavements overlain by asphalt. In terms of RCC a total asphalt thicknesses between 50 mm and 120 mm in combination with engineered transverse crack spacing of 2.5 to 3.5 m were found to control reflective cracking (Jofre, 2001).

An additional benefit to reducing the crack spacing was that it kept the cracks narrow with good aggregate interlock. The narrower the crack, the greater the load transfer achieved across it (Pittman, 1994). Other variables include temperature and specifics of the RCC mix design including maximum aggregate size (Pittman, 1994).

International experience at AECOM includes the design of asphalt surfaced RCC trials for highways in eastern Europe and the UK.

High volume high speed road applications of RCC surfaced with asphalt have been successfully built and operated in the US. US-78, Ladson is a state route with heavy truck traffic (ADT is 41700 with 10% trucks) and a speed limit of 70 km/hr. In 2008, the existing pavement was replaced by South Carolina Department of Transport with 250 mm RCC and 50 mm HMA. Project length was approximately 0.9 miles. More recent examples include US 83 Leakey where the Texas Department of Transportation completed its first mainline, high-speed RCC Federal Highway in November 2016. The route is a heavy truck route servicing quarries and oil/gas activities with a speed limit of 90 km/hr. The 42000 m^2 of 200 mm depth RCC was placed in a 3 week period averaging nearly 0.5 lane miles per day. The road was opened to traffic within days of paving.

2.3 Technology level of RCC in the UK

RCC was introduced to the UK in 2002, the material has been used mainly to construct hardstanding areas for the waste industry, bulk materials handling and HGV parking (Figure 1). Figure 1 shows an unsurfaced RCC used as a heavy duty pavement at composting facility (bottom left, photograph courtesy of Cemex), unsurfaced saw cut and sealed heavy duty RCC pavement for container handling (bottom right, photograph courtesy of Tarmac) and the construction of a large heavy duty pavement over an unbound foundation (top, photograph courtesy of Aggregate Industries). These examples are similar to the unsurfaced applications of RCC with subsequent development branching into unsurfaced low speed or surfaced highway applications.

Figure 1 Heavy duty RCC pavement constructions in the UK

Development of heavy duty RCC pavement constructions into highway constructions suitable for the requirements of the Highways England network required additional considerations. These are primarily linked to the typical requirement for high speed skid resistance, for which asphalt surfacing was initially considered the primary solution. The nature of these sites being long linear features means that transverse cracking of RCC is an important point of detail. Figure 2 shows the typical paving activities for RCC construction for a highway scheme. The above points mean that the potential for unacceptable reflective cracking through the asphalt from joints/cracks in the RCC is a design and maintenance consideration for this type of pavement.

Other countries went through the same development process for RCC in highway pavements (see Section 2.2). In the UK a Highways England network demonstration of RCC constructions overlayed by varying thicknesses of asphalt was constructed on the A11 Fiveways to Thetford Improvement scheme by Balfour Beatty and Tarmac. The scheme was opened in December 2014 and was monitored by AECOM in 2017. The demonstration areas had no visual or pavement defects.

In parallel to this work Highways England and industry (primarily represented by Britpave) undertook the initial development work on revision to the MCHW and DMRB for specific provision of RCC. This work was independently reviewed by AECOM as part of this contract, with additional analytical works undertaken to validate specific points of detail such as asphalt overlay thickness, pre crack spacing and thickness design.

Figure 2 Highway construction

The rest of this document gives an overview of the inputs to the DMRB and MCHW from the above process to support the use of RCC on the Highways England network.

3. Features and properties of RCC as a material

This section gives an overview of RCC as pavement material for use on the Highways England network and details the main technical considerations for RCC as a material.

These points are then included in consideration of mix design and production (see Section 4), which forms the basis for the draft MCHW Series 1000 Volume 1 and Volume 2 clauses for the specification, production, installation and testing of RCC.

3.1 Material description

RCC has similar constituents to conventional concrete. However, they are mixed in different ratios and increasingly incorporating fly ash or other Portland cement substitute (PCA, 2006). The material is a mix of cement / cement substitute, water, sand and aggregates and other additives if deemed necessary. The mix contains much less water than a conventional concrete mix, this means that the mix is drier and has no slump.

RCC does not flow like conventional concrete, is not transported to site in mixers, is not consolidated with a vibratory poker and does not require formwork for placement.

RCC typically comes to site in conventional uninsulated trucks, it is typically laid by pavers and is compacted by vibratory rollers and/or Pneumatic Tyred Rollers (PTR). Although similar in nature to asphalt paving, RCC benefits from the use of specialist plant which is discussed further in Section 6.

The strength of the finished material is reliant on the constituents of the mix and the level of compaction that can be achieved. One element the RCC and concrete share is the need for a curing to develop sufficient long term strength and durability. However, RCC has the potential to be trafficked significantly earlier in its life than concrete. This aspect is termed immediate trafficability (Britpave BP/14, 2005). In context of RCC on the Highways England network the design RCC for immediate trafficability has potential for significant programme benefits, minimising curing times on site prior to asphalt overlay. This is discussed further in Sections 4 and 6.

The following specifications are typically drawn upon to cover the required testing, constituent and mix requirements:

- Hydraulically bound mixtures — Specifications Part 1: Cement bound granular mixtures BS EN 14227-1.
- Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction BS EN 13242
- Cement — Part 1: Composition, specifications and conformity criteria for common cements. BS EN 197-1.
- Test methods for Unbound and hydraulically bound mixtures in parts of BS EN 13286. These standards include sample preparation and mechanical testing.

A gap in the above set of documents is for testing on site during installation of RCC. This testing would include control and also performance testing.

The above standards and specifications were taken forward into the development of the Specification for RCC. The initial work by industry was also undertaken to provide appropriate requirements for testing on site during installation of RCC. These points are further discussed in Sections 4 and 6 of this report.

3.2 Strengths and benefits

Material characteristics and the associated benefits of RCC for the construction of pavements are outlined in Table 1.

It is important to note that the RCC must be well designed, specified, controlled and constructed to achieve the positive material characteristics. Therefore, these are all points for consideration during the development of the specification for inclusion in the MCHW.

Table 1 Strengths and benefits adapted from PCA publication and BP/55

Material characteristics	Potential benefits
High flexural strength can be achieved with a typical range between 4 MPa to 6 MPa	Supports heavy, repetitive loads and can span localised soft subgrade areas.
High compressive strength (30 MPa to 60 MPa)	
High shear strength developed to enable immediate trafficking	RCC designed for immediate trafficking eliminates early life rutting during overlay or use by construction plant
RCC can be designed for high density, low absorption	This provides good durability even under freeze-thaw conditions without a need for air entrainment. It also mitigates water seepage through the pavement.
Low water content, low water/cement ratio	Reduces permeability, and enhances durability and resistance to chemical attack. Low shrinkage and thermal expansion when compared to standard concretes.
Aggregate interlock	Provides load transfer through high shear resistance at joints and uncontrolled cracks. This coupled with low thermal movement means no dowels required. This can also allow early trafficking.
No steel reinforcing or dowels	Speeds up and simplifies construction, reducing costs.
No forms or finishing	Speeds up and simplifies construction, reducing costs.
Crack control joints can be installed by wet- formed induced cracking	Efficiency saving versus conventional sawn and sealed joints.
If required, joints may be sawn and sealed conventionally	Reduces the risk of degradation at construction joints.

4. Mix design and production

4.1 Considerations for RCC mix design

The mix design and materials must be chosen and tested for consistency so that desired performance in these tests can be achieved. Durability is a complicated subject interrelated to various parts of the design, material and construction specification. In terms of RCC the main durability test is on the mixture, as is the normal practice for hydraulically bound base layers.

The following sections detail considerations linked to the above.

4.1.1 Aggregate properties and grading

RCC consists of up to 85 % aggregates with aggregate interlock being important for:

- material strength (especially if early life trafficking is required), and
- load transfer across transverse joints (pre cracks)

The correct selection and grading of aggregates is a key element of a successful mix design (Table 2). This is also important to achieving relatively high strength for RCC versus other types of CBGM, and also ensuring durability. In simplistic terms aggregates which give mechanical durability, poor interlock and/or are prone to fragmentation are precluded by Points A to C. Points D and E relate to ensuring chemical durability within the mixture. Point F is important for a range of reasons including durability (sensitivity to water) and also mechanical performance.

Table 2 Restrictions for the aggregates for use in high volume, high speed roads from Specification for Highway Works (SHW) Series 1000

Point	Requirement	Categories for aggregate properties
A	Crushed or broken particles in coarse and fine aggregate	C100/0 (crushed gravels are not permitted) Manufactured and recycled aggregates are not permitted
B	Resistance to fragmentation of coarse aggregate	LA35 minimum
C	Magnesium sulfate	MS18
D	Total sulphur content	S1 (Where the Contractor is able to provide evidence of mixture stability over an extended period then the Overseeing Organisation may consider the use of higher limits.)
E	Acid-soluble sulfate content	AS0.2 (Where the Contractor is able to provide evidence of mixture stability over an extended period then the Overseeing Organisation may consider the use of higher limits.)
F	Fines quality	Aggregate passing 425 μm shall be non-plastic as defined by and tested in compliance with BS 1377-2

In terms of aggregate grading industry feedback was for an aggregate grading onto which cement could then be added (see Table 3). Options are included for a 0/14 and 0/20 mixture which are suitable enabling the installation of dense thick layers, while mitigating the risk of segregation which is typically associated with larger aggregate sizes. The grading limits are in addition to the criteria for aggregates outlined in BS EN 13242.

Table 3 Aggregate grading limits for a maximum aggregate size of 14 mm and 20 mm from SHW Series 1000

Sieve mm	Percentage passing by mass			
	0/14		0/20	
	Minimum	Maximum	Minimum	Maximum
31.5	100	100	100	100
20	100	100	90	100
14	86	100	78	94
10	72	95	62	86
4	52	74	38	59
2	41	61	28	48
1	30	50	19	39
0.5	20	37	15	31
0.25	11	26	9	23
0.12	6	15	6	15
0.06	2	10	2	10

In addition to the restrictions listed, aggregates with an elongated shape are not recommended due to potential poor packing resulting in lower density which is linked to durability and strength. Unwashed rock fines with up to 10 % passing the 63 micron sieve can enhance the packing as long as they are non-plastic. The aggregates should be angular, strong and non-reactive with the grading allowing for a tight packing of the matrix to achieve the specified performance from strength and density testing. The above points are all covered in the Specification.

4.1.2 Cement and Additive properties

The cement, whatever allowable type it is, has the dual purpose of binding the mixture when cured and acting as a micro-filler to give a dense matrix. The cement should conform to BS EN 197-1. There is a range of cement types that can be used with a minimum cement content specified (Table 4).

Table 4 Cement blend options and minimum contents from SHW Series 1000

Cement and combinations	Minimum Cement or Combination Content
(a) Portland cement CEM I conforming to BS EN 197-1	270 kg/m^3
(b) Portland-slag cement CEM II/A-S and CEM II/B-S conforming to BS EN 197-1 (c) Portland-fly ash cement CEM II/A-V and CEM II/B-V conforming to BS EN 197-1 (d) Pozzolanic cement CEM IV/A (V) conforming to BS EN 197-1 See NOTE 1	270 kg/m^3
(f) A BS 8500-2 combination of Portland cement CEM I conforming to BS EN 197-1 with not more than 35% fly-ash for use as a cementitious component in structural concrete conforming to BS EN 450-1 (SEE NOTE 2)	270 kg/m^3
NOTE 1: CEM II/A-V has a maximum siliceous fly ash content of 20% CEM II/B-V has a maximum siliceous fly ash content of 35% CEM IV/A (V) has a maximum siliceous fly ash content of 35% NOTE 2: Siliceous fly ash conforming to EN 14227-4 may be used where it meets the BS 8500-2:2015 Annex A compressive strength requirements.	

The use of PFA in a cement combination can have technical benefits for durability (in terms of limiting porosity) and mechanical performance. This is evidenced by an established track record of use in RCC and also hydraulically bound mixtures (HBM) which are currently permitted in the MCHW and DMRB for pavement base and subbase applications.

4.1.3 Water and admixtures

Potable mains water can be used without testing as it will not contain anything that would adversely affect the mix performance. Water from other sources should be tested in accordance with BS EN 1008. Admixtures that are used in conventional concrete can be used in RCC but will require higher doses due to the low water cement ratio. RCC does not usually require admixtures with the exception being retarding mixtures if it is being transported long distance to extend the working life of the mix.

4.2 Mix design method

There are various methods available for mix proportioning for RCC but the most widely used is the Soil Compaction Method (PCA_1). This proportioning method involves establishing a relationship between the density and water content of an RCC mixture to obtain the maximum density by compacting samples over a range of water contents. The approach specified for HBM in Series 800 of MCHW is recommended for determining the optimum moisture content and maximum dry density using the vibratory hammer method described in BS EN 13286-4. The goals of the mix design is to produce an RCC that:

1. Provides sufficient volume of paste to coat aggregates and fill the voids between them
2. Has a mix that can produce the required mechanical strength and elastic properties
3. Is workable and can be easily compacted to achieve the required density

Research has shown that the in-situ density can be higher than predicted in the laboratory at optimum moisture content (PCA_2). If the mix is placed at water contents slightly above optimum this can give better compaction of the lower half of the layer when compacted from the surface.

The mix design must consider material variability, mixing variability and site conditions. These variables should be allowed for by a factor of safety for mix design strength. The design should also consider that the mix will be produced on the wet side of its optimum water content to enable compaction on site. The target water content is typically adjusted during the works on the basis of site conditions and response of the material during compaction.

The mix design should deliver an RCC mix that determines the mix constituent quantities required to give the desired margin over the design strength. This strength should be achievable while giving an achievable field density. The technical requirements for this are well established in the UK and have been transposed over to the RCC specification and associated guidance in the MCHW.

4.3 Production

The mixing plant is key to the economic viability of an RCC pavement and as such should be chosen to match the size of the project and the required production volumes needed to supply the laying operations. In comparison to conventional concrete mixing, RCC requires more mixing effort to distribute the water and cement evenly throughout the mix (PCA_2). Therefore, the preferred mixing plants are continuous flow mixers such as pugmills and horizontal shaft mixing plants that give high mixing effort and production rates. Higher production rates can benefit the continuous paving of materials avoiding delays in compaction and/or formation of additional construction joints.

The specification is not prescriptive about the type of mixer to be used, but it does limit options to mix-in-plant method using batching by mass, in accordance with SHW Clause 1055. In addition, a minimum of two aggregate fractions should be used each with a separate feed hopper. This is a sensible requirement to control aggregate grading within the mixture which has relatively onerous limits for RCC versus HBM used in lower layers of a pavement.

The plant should operate a production quality management system which follows the guidance in BS EN 14227-1 Annex B with automated recording and data collection system.

The plant should discharge the mix in such a way that there is no segregation of the mix. Unlike conventional concrete once the mix is discharged there will be no continuous agitation, so this is an important part of the process; therefore, segregation in the truck could be reflected in the paved RCC.

The plant should have sufficient capacity to fill the trucks used to transport it to site in a reasonable time period as the permitted construction period starts when the first RCC is poured in the truck. The production process should deliver a well-mixed and homogeneous RCC discharged into the delivery truck in a reasonable time.

Typical examples of UK based mobile plant used for the production of RCC are shown in Figure 3. Further guidance on the production of RCC can be found in Britpave BP/55 (2013).

Figure 3 Typical production plant used for RCC (photographs courtesy of Aggregate Industries and OCL)

5. Pavement Design

5.1 Design Method origin

The design method used to determine the required depth of RCC needed for different traffic loading levels is based on an analytical pavement design method. RCC is to be used in conjunction with 90 mm total asphalt thickness (50 mm thickness of binder course and 40 mm thickness of surface course) for Highways England roads.

The design considerations for mitigation of non-structural reflective cracking is discussed in Section 5.2

An overview on structural design and derivation of the design charts for inclusion in the DMRB are given in Sections 5.3 and 5.4.

5.2 Reflective cracking

The total thickness of asphalt required to mitigate the risk of unacceptable reflective cracking is linked into the specified pre crack spacing (Section 6) and RCC material specification (Section 4).

In the network trials of RCC the thickness of asphalt overlay was selected following a series of design iterations using a range of asphalt thicknesses and material types. A limitation on the analysis is that at least two layers of asphalt are required to ensure acceptable ride quality for consideration on the Highways England network. This is based on the current understanding of paving construction which can be used for RCC. It is likely that future developments in placement of materials and level control could mean this assumption is revisited.

The analysis of thickness was done using propriety in-house software at AECOM. The results of this have been validated to date during the monitoring of the RCC network trials. These are also validated by work undertaken for the use of RCC in similar scenarios as detailed in Section 2.

Material selection for the asphalt layers is another consideration. The surface course is open to selection based on the current Highways England standards for safety, noise and durability requirements.

The binder course is limited to a Hot Rolled Asphalt (HRA). The benefit of this is to assist in sealing the RCC surface and mitigate the risk of water penetration into transverse pre-cracks and joints. Rut resistance of the HRA is required to be that for very heavily stressed sites, i.e. requiring very high rut resistance to mitigate the risk of this layer rutting above the underlying RCC.

The pavement structural design life incorporated the structural contribution of the 90 mm total thickness of asphalt. This is detailed in Section 5.3.

5.3 Modelling and properties assumed

The pavement life is calculated given the depth of RCC and 90 mm asphalt layers by modelling a typical tyre load and the fatigue life of the pavement for that loading. There are two design lines given: one for a foundation Class 3 and one for a foundation Class 4. Both of these foundations require a bound subbase which is consistent with the network trials of RCC to date.

It is recognised that the use of unbound foundations (foundation class 2) is common for RCC used in heavy duty pavements and that this has a proven track record. This could be a future development for RCC on the Highways England network.

An overview of the design method used is that it determines the fatigue life of the pavement based upon a combination of factors that are assumed for the modelling conditions.

The thickness design is a function of the expected wheel loads, volume of trafficking, concrete strength and characteristics of the supporting foundation. These factors are important to understanding the applicability of the pavement design and how the results should be used. In the model the depth of the surface course is not relevant, as the total asphalt depth is a minimum of 90 mm. The binder course is assumed to be HRA as per the details in Section 5.2. The RCC mixture designation is C40/50 for which the design assumes:

- RCC Flexural Strength of 5.0 MPa
- RCC Modulus E = 50,000 MPa
- RCC Poisson's Ratio **ν** = 0.20
- RCC Fatigue Life = EXP((Stress Ratio – 0.9157)/-0.039)/10^6

An example of a calculation using multi-layer linear elastic analysis for the pavement depth:

- Wheel load 40 kN and contact radius 151 mm
- 40 mm Thin Surface Course E = 2,000 MPa **ν** = 0.35
- 50 mm HRA Binder Course E = 3,100 MPa **ν** = 0.35
- 180 mm RCC E = 50,000 MPa **ν** = 0.20
- Foundation Class 3 E = 200 MPa **ν** = 0.35

Calculated tensile stress at the bottom of the RCC layer = 1.10 MPa

Calculated stress ratio (= induced stress/flexural strength) = 0.220

Calculated Life = EXP((Stress Ratio -0.9157)/-0.039)/10^6 = 56 msa

The above was the main method used to determine the standard design charts shown in Section 5.4. However, they were also checked using alternative methods of RCC thickness design.

5.4 Depths recommended

A number of different combinations of RCC depth with the properties listed in the previous section were modelled to give recommended depths for different levels of traffic loading. The graph allows for the appropriate depth of RCC to be chosen for the calculated traffic loading for a project on the Highways England network (Figure 4).

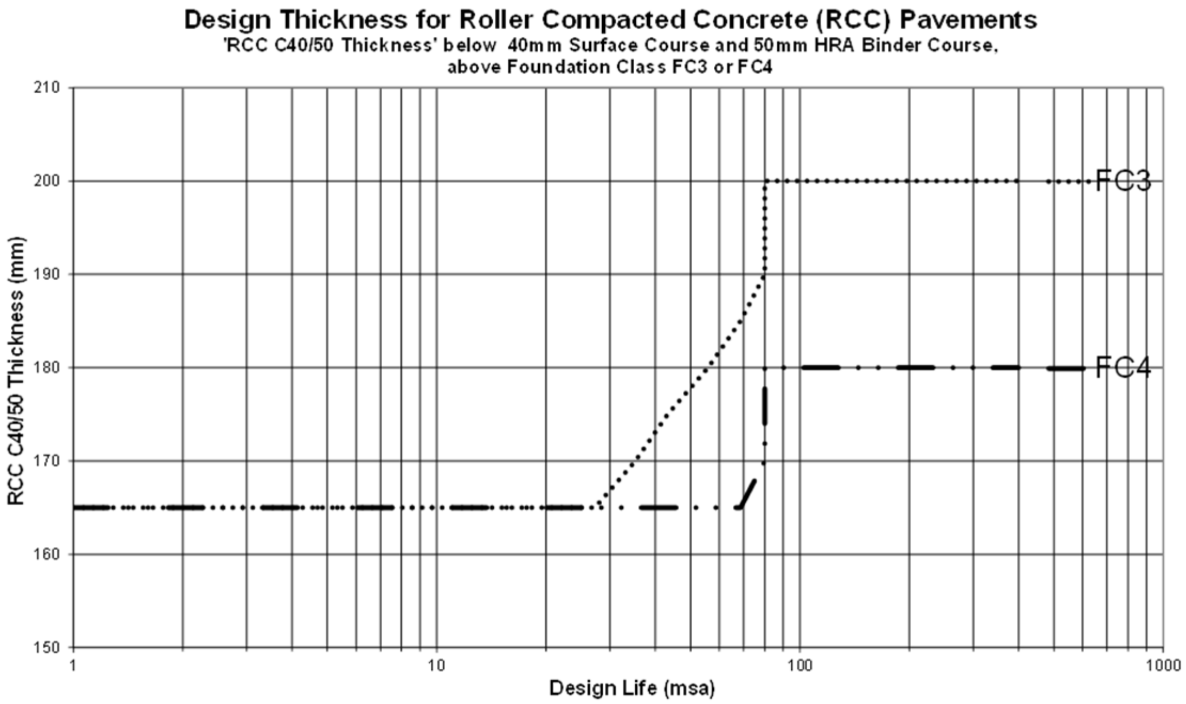

Figure 4 RCC design graphs for foundation Class 3 and 4

The lowest nominal layer thickness of 165 mm was selected on the basis of achievable laying tolerances using the method of installed detailed in Section 6, and incorporated into the MCHW.

6. Construction and laying method

The following section gives an overview of considerations initially developed by Highways England working with industry for inclusion with the MCHW.

6.1 Transportation to site

RCC mix is typically transported to site in trucks that should be covered with tarpaulins or other suitable coverings (Figure 5) in order to avoid excessive moisture loss (in hot weather) or excess moisture ingress (raining heavily). Changes to the moisture content can cause problems in placement, compaction, and subsequent in-service performance. These points are covered in the MCHW by requirements on surface finish, water control, compaction and wet weather working.

Figure 5 Rigid body truck tipping directly into paver hopper and discharged material in paver hopper

Other aspects of the works are linked to ensuring continuity of paving and avoiding defective work. These points are typically covered with the contractor's method statement and quality control plan. These include logistics of production, supply and paving rates; and workmanship to avoid drying out or segregation of RCC.

6.2 Preparation of substrata

The preparation of the substrate for which RCC is to be paved on is as per requirements he current MCHW specification.

6.3 Paving

RCC should only be laid on the Highways England network with high-compaction paving equipment with a high compaction screed. This will result in minimal rolling to achieve the required compaction of the mix (Figure 6).

The less compaction required from rolling will help to maintain a good surface evenness as the regularity is difficult to control if there is a large roll down of the pavement depth. The laying machine should be tracked and not wheeled to help keep an even layer. The compaction effort provided by conventional asphalt paving machines is not sufficient to achieve the required pre-rolling compaction levels and should not be used. The minimum compacted layer thickness will be 165 mm to a maximum of 200 mm. The RCC shall only be laid in one layer, multi-lift RCC is not permitted. This makes it very important that the paver must be capable of attaining the thickness, lines and grades indicated on the plan, and produce consistent compaction and compliance with surface level tolerance.

Figure 6 Paver laying RCC with grooving and groove filling taking place behind it

6.4 Inducement of joints

Transverse pre-cracking should be formed at 2.5 m centres after initial compaction by the paver (Figure 6). The specification for this was developed by Highways England working with industry and has been included in the MCHW. The transverse crack spacing selected is a balance between maintaining structural integrity of the layer and having sufficiently close cracks to control the potential for reflective cracking.

6.5 Roller compaction

The roller compaction of the laid and grooved material is the final part of the mechanical laying and compaction process. As a high compaction paver has been used for laying this should minimise the amount of rolling that is required. The initial rolling should be carried out by vibratory rollers followed, if required, by a PTR and finished with a static roller, if necessary, to give an even finish (Figure 7). The rolling should take place as soon as possible to reduce moisture loss or ingress depending on weather conditions as it is part of the permitted construction period (Britpave BP/55, 2013). This compaction is important as it will provide the material strength for early construction trafficking that would be associated with immediate asphalt laying over the RCC (Britpave BP/14, 2005).

Figure 7 Twin drum roller followed by PTR compacting freshly laid RCC

The recommended approach is to determine an optimum rolling pattern that will result in the specified minimum density being met in the least amount of time and passes. This can be done in a trial area where the rolling pattern can be tried and final testing of density and strength of cores compared to determine effectiveness. This trial area will be expensive to construct and should be incorporated into the permanent works. Testing of density, after compaction, can be performed in the works on an ongoing basis by using a nuclear density meter. These tests should be performed in the wheel tracks.

6.6 Curing

Curing is an extremely important factor in the ultimate strength and durability of RCC and ensuring an intact upper layer. Curing benefits the pavement by allowing the concrete to develop the design strength and by preventing scaling, dusting, and ravelling of the hardened surface.

Curing shall be undertaken as soon as practicable, and the curing compound shall be applied prior to drying of the surface. It is advised to apply more than would be required for conventional concrete.

These considerations were included in the MCHW.

6.7 Weather Precautions

The following section details condition on weather precautions for the installation of RCC. These points have been included in the specification initially developed by Highways England and industry.

6.7.1 General weather requirements

The construction period, in degree hours, shall be the summation of the products of the average air temperature above 3ºC (T ºC) and time for each period (t hours): i.e. construction period limit =Σ(T.t). If the air temperature during the interval, t, fluctuates by more than 4ºC, interval t shall be re-calculated. The construction period should be continuously reviewed in relation to projected changing weather conditions and adjusted accordingly. This is essential to allow ongoing production in changing conditions and maintain quality.

RCC paving works are likely to have a large output versus those of concrete. As per concrete RCC needs to be correctly protected during its early life from cold, hot, windy and wet weather. For large paved areas, it is often impractical to apply technologies used for concrete, such as insulation blankets and/or polythene foam sheets. Therefore, with RCC details of the curing membrane and requirements around cold, hot and wet weather were included into the specification.

In addition, the porosity of the RCC surface is a consideration for potential early life frost damage prior to overlay with asphalt, therefore the integrity of the curing membrane must be maintained to prevent possible ingress of surface water. Experience with unpaved RCC is that once it has cured, is that it is a durable hardwearing surface.

6.7.2 Cold weather

The rate of hydration of cement binders slows down at low temperatures and hydration can stop if the mixture temperature falls to close to 3°C. If freezing occurs in a mixture which has yet to attain full strength it may disrupt the bond between the binder and the aggregate. The formation of ice lenses can displace aggregate from RCC mixtures. The RCC mixture chosen should develop sufficient tensile strength to resist internal freezing, if it is likely to be subject to temperatures close to 3°C. Strength develops relatively quickly in an RCC mixture with minimum cement contents, so it is unlikely to be affected by low temperatures. A risk assessment approach to evaluate and define appropriate weather and construction time criteria for RCC by considering:

- the depth of cover provided by the overlying layers
- the type and durability of the aggregates used in the mixture
- the likely strength gain of the mixture prior to overlay
- the site location

- the likely construction date
- timely application of the curing membrane to prevent ingress of water

6.7.3 Hot weather

During periods of hot weather or windy conditions, special precautions should be taken to minimize moisture loss due to evaporation. High temperatures will increase the rate of evaporation from the RCC prior to compaction, reduce the working time (permitted construction period) and create problems retaining sufficient moisture at the surface to ensure full hydration can take place.

6.7.4 Wet weather

Rain can degrade RCC mixtures, particularly if the mixture has a high proportion of fine aggregate or if the mixture is to be trafficked soon after laying. If the rain is light, it may be possible to continue laying by adjusting the amount of water added during production of the mixture.

Transverse and longitudinal day joints should be formed before commencing further work by sawing vertically to the full depth. The fresh material should be laid to abut against this day joint. This form of jointing should be kept to a minimum as it will be an area of weakness in the pavement.

6.8 Surface tolerance and defect rectification

The restriction to lay RCC in one layer on the Highways England network makes the control of the surface regularity critical to the performance of the pavement as a whole. The inclusion of 90 mm of asphalt over the RCC creates a suitable ride quality for a high speed road, as it smooths minor irregularities in the RCC surface finish.

If rectifications are required then they should take place during the permitted construction period and the water requirements should be maintained within acceptable limits. If the rectification cannot be completed successfully within the permitted construction period then a minimum length of 15 m and one lane width should be removed and replaced using the jointing described in section 6.4.

6.9 Asphalt layers

The surface texture of RCC can be relatively low surface texture and suitable for parking and road pavements where the traffic speeds are relatively low (< 60 km/hour).

However, there are pavement surface characteristics for which RCC has not demonstrated satisfactory performance. These characteristics are surface condition (rough textured and ravelling), skid resistance (attributable to difficulty in texturing), and surface smoothness. It is because of these concerns that an asphalt overlay is recommended. Thus, RCC will provide the primary structural support for the roadway, and the asphalt overlay will provide a suitable riding surface.

Depending on the early bearing capacity of the RCC, asphalt layers can start being laid immediately. An immediate bearing index (IBI) of greater than 50 of the constructed layer should be suitable for immediate trafficking for the purpose of constructing subsequent layers. The prime coat bitumen emulsion for the asphalt can be used as the curing membrane for the RCC layer. The asphalt layers are to be laid in accordance with specification for these layers; the RCC should not change how these layers are laid.

7. Performance and maintenance

7.1 Serviceable life

RCC like all designs used on the Highways England network will be designed for 40 years for new build and 20 years for maintenance. However, RCC like conventional concrete would be expected to be a low maintenance material option that has longer term durability compared to asphalt. The asphalt layers on the RCC will require routine replacement as would be similar with any other pavements. This maintenance is important for the long term performance as it creates a barrier between the RCC and traffic loading and the environment.

7.2 Failure mechanisms

In the design process the failure mechanism of RCC that is considered is tensile cracking at the bottom of the concrete when subjected to axle loading. In the field, the areas of concern for long term durability will be at the cracking inducement and joint locations. These are areas of weakness and where water can enter the pavement. These areas will degrade faster than the rest of the pavement and will probably be critical to if or when maintenance of the RCC layer will be required. The best way to guard against this is to assure that the asphalt layers are replaced when they become ineffective at sealing the RCC.

7.3 Maintenance repair methods

The main concern on high volume roads is to minimise the number and duration of maintenance interventions to reduce the impact on customer's journeys. The combination of RCC and asphalt helps with this concept. The 90 mm of asphalt can be removed and replaced in a night time closure minimising disruption to the network. If there is damage to the RCC layer that needs repairing it will require a longer closure but this is also true of other materials. The minimum treatment length should be 15 m and one traffic lane width for the RCC layer with the subsequent asphalt layers having suitable lap lengths and joint steps.

8. Summary

The research and development to allow technical innovation associated with the introduction of RCC as a standard option into DMRB and MCWH Series 1000, Volumes 1 and 2 has been completed.

Key points of consideration for adopting asphalt surfaced RCC pavements were:

1. Developing confidence in the track record of RCC both as an available material option and its in-service performance both internationally and in the UK
2. Highways England working with industry to develop the basis of a workable robust specification for RCC materials and installation
3. Independent review and validation of the industry outputs for the specification, construction and design of RCC pavements
4. Network trials to confirm acceptability of the construction solutions with RCC through test and demonstration
5. Monitoring early life in service performance of trials to confirm acceptability of the RCC designs
6. A holistic review of the technical risk associated with the adoption of RCC into the DMRB and MCHW overall (including pavement design, material(s) and construction solutions) and technical review to ensure they were appropriately addressed to facilitate generic network approval

On the basis of the above standard design charts for the DMRB and detailed specifications for the MCHW have been produced. It is important to note that the relevant parts of the DMRB and MCHW for RCC have relatively high performance requirements versus guidance on materials specification and pavement design using RCC for other applications outside of the Highways England network. Examples of these include heavy duty pavements or for unsurfaced slow traffic speed applications (for example lorry parks).

9. Acknowledgements

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