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Damages of Orthotropic Bridge Deck Surfacing: Forensic Investigation, Remedial Work and Performance Monitoring

Iswandaru Widyatmoko [a,b*]
[a]*Transportation and Infrastructure Materials Research, AECOM, Nottingham, United Kingdom*
[b]*Department of Civil Engineering, Universitas Pertamina, Jakarta, Indonesia*

**Corresponding author: daru.widyatmoko@aecom.com*

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ABSTRACT

Conventional mastic asphalt typically lasts for more than two decades when being used as bridge surfacing. However substantial increase in heavy goods traffic and higher axle loading has led to some severe cracks in the surfacing during the first ten years since opening to traffic. A forensic investigation into the defects was subsequently carried out. The investigation comprised site inspection, reviewing available records, laboratory testing, designing new surfacing system and recommending remedial actions. The site inspection identified structural and functional damages, which were subsequently assessed in the laboratory on samples taken from site followed by detailed analysis. Laboratory assessments included stiffness, tensile strength and rheology of the existing mastic asphalt surfacing and the waterproofing layer. These suites of testing were followed by Finite Element Models (FEMs) which were developed specifically to analyze movements of the deck, including the cantilever and the main decks, for a range of traffic levels and speeds, considering the mechanical properties determined from the laboratory tests. From the review of literatures and worldwide case studies, three alternative surfacing system options were identified. Prediction of the residual life of the existing surfacing and the projected life of the recommended replacement systems were analyzed. The effect of super single wheel loading on the proposed system was also assessed. Based on the relative performance of these options, recommendations were presented to improve the surfacing design for use in the interim maintenance and remedial works. Follow up works included monitoring the in service performance of the interim solution since opening to traffic. For the future major rehabilitation works, three alternative options have been advised to replace the current surfacing system. The benefits of each of these options have also been presented to assist with decision making, in consideration of the cost and the technical side.

Keywords: Surfacing damage; forensic investigation; mastic asphalt; FEM; performance monitoring

INTRODUCTION

Brown (2007) reported that the idea for a bridge connecting cities of Plymouth and Saltash in England was first conceived in 1823 but it was not realised due to financial and practical constraints. In the following century, there was substantially increased levels of ferry crossings between these cities, and that made the two neighbouring councils agreed on financing the construction of a road bridge, which was to be located precisely to the north of the historic Brunel's Royal Albert (railway) Bridge.

The construction work started in July 1959 and was completed in 1961. The original design was a bridge supported by suspension cables and a truss girder, with a reinforced concrete deck. The deck was made out of a concrete base covered with 20 mm steel plates and overlaid by 200 mm asphalt surfacing system, capable of catering three traffic lanes. The main span of the bridge was 335m long and the symmetrical side spans was 114m. Overall, it had a total length of 642m including anchorage and support spans. The main towers were constructed from reinforced concrete, are seated on caisson foundations and are 73m tall, with the deck suspended halfway up. The truss was 15.2m wide and 4.9m deep. Vertical locked coil hangers were at 9.2m, meeting at the truss' cross girders. Further information about the original design of the bridge can be found in a paper by Anderson (1965).

For a short time, the road bridge was regarded as the longest suspension bridge in the UK and was also the first to be built since World War 2 (Westgate, 2012). After nearly four decades of use, it was found that the road bridge would no longer be able to meet a new European Union Directive that bridges should be capable of carrying lorries weighing up to 40 tonnes. Furthermore, the traffic level was almost double of that in the original design (Cross et al. 2010). Nonetheless imposing restriction on traffic loading was not an option since it would damage the local economy. Therefore, it was decided that strengthening and widening of the bridge would be necessary to cater the considerable increase of road traffic.

The major strengthening and widening program were completed out in 2001. This program included the replacement of the main concrete deck with an orthotropic steel deck and additional new cantilever decks which were suspended on each side of the bridge. These new deck structures required lighter asphalt surfacing. In this work, the steel deck was overlaid by much a thinner, nominally 40mm thick mastic asphalt (MA), which was a specialised bridge surfacing system. The new layout was capable of accommodating four traffic lanes and one pedestrian/bicycle lane, as illustrated in Figure 1.

Due to increased number of structural and functional damages during the first 10 years since the strengthening and widening work, part of the surfacing system was replaced in the autumn of 2011. The adopted rehabilitation methodology, involving site investigation and performance monitoring, as well as recommendation for the future major maintenance, are described in this paper.

METHODOLOGY

Prior to the rehabilitation work in 2011, forensic investigations involving site inspection and laboratory testing were conducted. Samples of bridge deck surfacing system were removed from sites and were subjected to laboratory testing. Based on findings from the forensic investigation, a selection of surfacing material options was reviewed, and considered for the design of a new surfacing system. Furthermore, Westgate and Brownjohn (2010) suggested finite element models (FEMs) could be developed specifically for this bridge deck structure. In this context, movements of the decks (including cantilevers), were analysed for varying levels of traffic and speed, taking into consideration the mechanical properties of the surfacing systems. Prediction of the remaining service life of the existing bridge surfacing system and that of the recommended new surfacing system were subsequently made. Super-single wheel load effect on the proposed range of materials was also evaluated. Based on findings from these works, the choice of alternative materials and improvement to asphalt mix design were then recommended for the interim repair work.

A flow diagram describing the adopted methodology is presented in Figure 2. This methodology is also consistent with that adopted for other similar structure (Edwards and Westergren, 2001; Xiao et al. 2005).

SITE INSPECTION

As mentioned previously, there are four traffic lanes and one pedestrian path since 2001. Three traffic lanes are located on the Main Deck (Eastbound/EB, Centre/CT and Westbound/WB) and one on the North cantilever (NC). The CT lane serves two-way traffic flows, depending upon the nature of the flow and/or the time of day. One shared-lane for pedestrians and bicycles was located on the South Cantilever (SC). This traffic arrangement shows that the sides of NC and EB direction were potentially loaded by vehicles that are slow moving and/or stop when approaching the toll plaza. On the other hand, vehicles were moving faster and more freely in the middle lane (CT) and WB direction.

During the review of the initial site work (Widyatmoko & Elliott 2013), some of the following damages were found at the time of the site investigation, which included:

1. structural damage that required immediate or future treatment. This includes a number of cracks in the traffic path (EB), longitudinal and transverse cracks, shifting material from the roadside, blisters, and;
2. functional damage that covers the apparent surface irregularity and variations in the distribution of the chipping, transverse and longitudinal profiles.

These observed damages are not uncommon and similar issues have been reported for asphaltic surfacing systems on

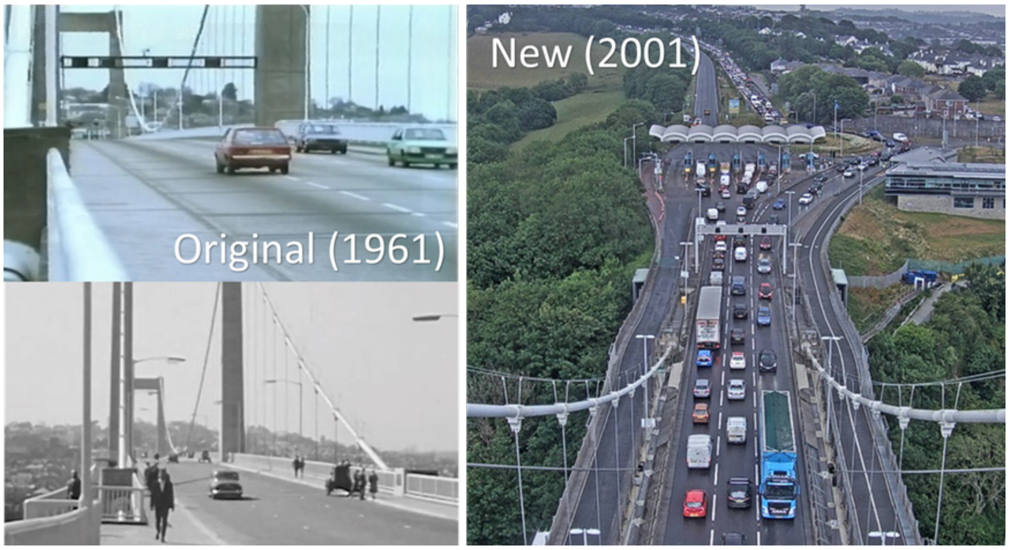


FIGURE 1. Transformation from the 3-lanes in the original design (1961) to the 5-lanes in the new design (2001)

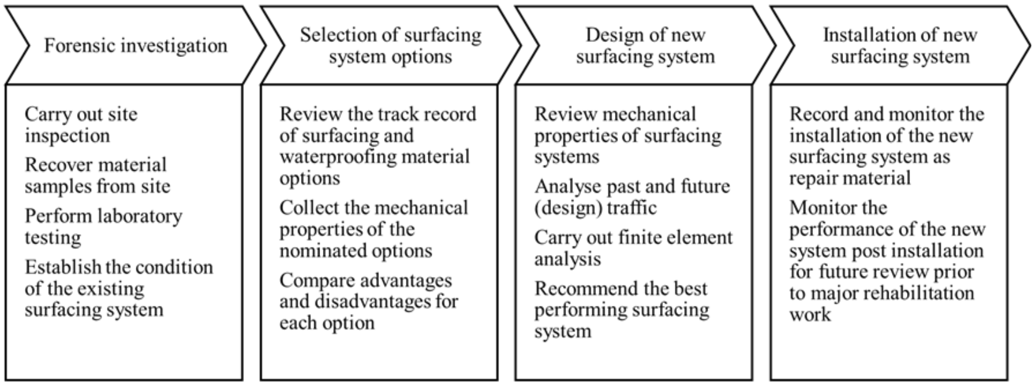


FIGURE 2. Methodology adopted for the rehabilitation work

suspension bridge (Wegan and Bloomstine 2004; Xiao et al. 2005).

LABORATORY TESTING

During a period between 2009 and 2016, samples of MA surface material and RBU waterproofing layer were taken from the road bridge. These samples were subsequently subjected to the following tests:

1. Visual assessment and core logging;
2. Stiffness modulus (*indirect tensile stiffness modulus,* ITSM) of the surfacing to BS EN 12697-26 (CEN 2018);
3. Indirect tensile strength (ITS) of the surfacing to BS EN 12697-23 (CEN 2017);
4. Shear modulus of the waterproofing layer to BS EN 14770 (CEN 2012).

The visual assessment and core logging revealed the structure of the original (2001) asphalt surfacing, as summarised in Table 1.

A summary of stiffness modulus and tensile strength test results conducted in 2009 can be seen in Table 2. For comparison, the subsequent test results, conducted in 2016, are also displayed in the same table, with the modulus value which can usually be achieved by newly installed MA surfacing.

The stiffness modulus and tensile strength values of MA (2009) turn out to be lower than those expected for MA (2016). It must also be noted that all these stiffness and tensile strength values remained lower than those typically expected for mastic asphalt materials with 50% TLA. In general, the target stiffness modulus at a temperature of 20°C for new MA would have been greater than 7000 MPa, and a value of around 9000 MPa was often assumed (Widyatmoko et al. 2005a and Liu et al. 2016). This indicates that the material taken from the field in 2009 experienced a decrease in stiffness modulus for up to 60% of the expected initial value. This can be caused by several things:

1. The installed material did not meet the job specifications, and/or;
2. Damage have had occurred on site.

The reduction in the stiffness modulus of the MA surfacing can result in reduced spreading ability to withstand traffic loading, and this can result in higher loading concentration at the waterproofing layer. Trends in the increased stiffness modulus and tensile strength values shown in Table 2 (i.e. from 2009 to 2016) can be associated with further hardening of the mastic asphalt samples. It should be noted that increased stiffness or tensile strength may generally imply better load bearing capability for bound layers over a stable substrate, in the context of relatively thin bound layers over a flexible substrate such as a steel deck, however, this may increase the risk for reflective and/or thermal cracking but reducing risk for deformation.

The RBU waterproofing layer contained a mixture of rubberized asphalt and fine aggregate mastic. A small sample of this waterproofing material was tested with a dynamic shear rheometer (DSR), to determine the shear modulus. The results, summarized in Figure 3, shows a dramatic reduction in the shear modulus of the RBU layer at the time of the test temperature exceeds 30°C; the measured value is approximately 100 times lower than the value of the MA. A very large difference, which is observed in the modulus of stiffness/shear value, becomes a point of weakness in the event of heavy load traffic along the slow lane. These results also show that the waterproofing layer is at risk of not having enough durability to withstand the shear loads.

SURFACING MATERIAL OPTIONS

Current surfacing system was considered not having adequate performance to withstand future traffic loads and should be replaced with an alternative better performing system. A desktop review was subsequently carried out to explore options for better performing bridge surfacing materials. The review found that Hicks et al. (2000), Huang et al. (2003), Van Bochove et al. (2008) and Lu at al. (2015) reported a variety of specialist materials which have been used for surfacing on long span bridge's steel decks in various parts of the world. These reports presented track records on field performance and maintenance requirements

TABLE 1. The composition of the original bridge deck surfacing systems (2001)

Chipping	0/14mm precoated
Surfacing	0/14mm mastic asphalt (MA) comprising 50% TLA (Trinidad Lake Asphalt), 38 mm thick
Waterproofing layer	rubberized bitumen underlay (RBU), 1.5 – 3 mm thick

TABLE 2. Summary of the modulus of stiffness and tensile strength – mastic Asphalt (MA)

MA condition	Stiffness modulus, ITSM (MPa)			Tensile strength, ITS (MPa)		
	-10°C	20°C	30°C	-10°C	20°C	30°C
Still new		9000		4 – 6	3 – 4	1.8 – 2.5
2009	20210	3430	1950	3.1	2.4	1.2
2016	27380	6060	3120	3.9	2.6	1.5

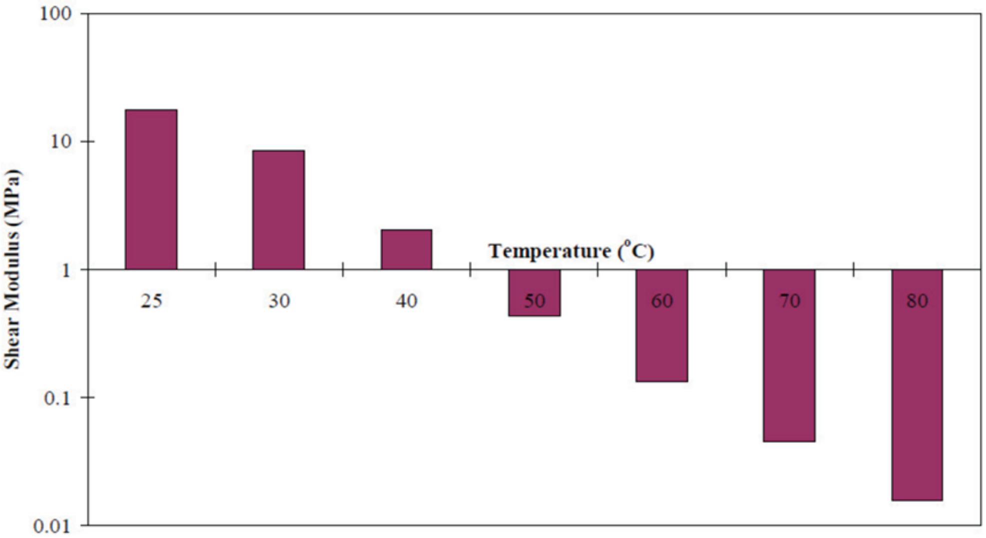


FIGURE 3. Shear Modulus (0.4 Hz) of RBU waterproofing layer

for different bridge surfacing materials. Amongst these materials, three were considered as potentially suitable for use as the candidates for new bridge surfacing system, specifically:

1. Polymer modified mastic Asphalt (PMMA);
2. Polymer modified Gussasphalt (GA), and;
3. Epoxy asphalt (EA).

These surfacing materials were derived from some families of standard asphalt materials to BS EN 13108 series but incorporating proprietary modified binders which were specifically designed for road bridges.

PMMA is composed of suitably graded limestone aggregates bound together with modified bitumen (natural asphalt such as TLA and/or polymer modified bitumen), to make a dense material with virtually no voids. It flows at laying temperature, then it is spread (rather than rolled) and does not require compaction. It has higher resistance to degradation from weathering than normal bituminous materials, as a result of its low void content and relatively high binder content. It can be used as either a base layer or a surfacing course, the latter with pre-coated chippings (PCC) added to it to give it a surface texture. Service life expectancy is typically 25 years.

Discussions about the characteristics, benefits and advantages of PMMA and its interactions with TLA have been discussed in detail by Widyatmoko et al. (2005b) and Lu et al. (2016). Some key beneficial properties are: (a) exceptional level of impermeability; (b) high stiffness (between 6000 – 12000 MPa at 20°C); (c) high resistance to rutting; (d) long fatigue life; and (e) good recyclability. There are however some disadvantages, which include: (a) requirement for high quality bond coat (polymer modified tack coat), particularly when applied to non bituminous waterproofing; (b) susceptible to cracking at discontinuities (for example, at bridge joints); (c) application of PCC using traditional plant is to a degree difficult to control and laying in exposed conditions risks poor PCC embedment and can risk having low surface texture and/or material loss, and (d) must be laid at a very high temperature at which the polymer may degrade. If the polymer degrades, it will destroy the material's good mechanical properties; hence the asphalt has to be finished / compacted very close to 180°C. The use of heat stable and compatible polymer modifiers is very important.

GA has its origin in Germany and is, apart from the production method, part of the family of mastic asphalt materials according to BS EN 13108-6. Hence today it often is used in Europe under the name of Mastic asphalt (MA). The high content of hard, or modified, bitumen and the high content of limestone filler produce an impermeable asphalt which must be finished by means of a paver specially designed for GA, such as by a rail mounted paving/finishing machine, in order to achieve a smooth profile and an even surface (Aeschlimann 2012). Like conventional MA, it is finished without compaction and has air voids of less than 1%. Typical stiffness modulus (tested to BS EN 12697 – 26) of this material is 5500 – 6500 MPa at 20^{o}C. PCC are embedded into the surface by means of static rollers to create a positive texture with high friction.

GA offers all the advantages given by PMMA plus the following added benefit as discussed by Kandahl and Mellott (1977), Ripke and Ehlert (2016), Luo et al. (2017; 2018) and Zou et al. (2020), such as: (a) fast application rate; (b) potentially seamless, with no longitudinal joints, as all lanes may be laid in one pass; (c) ability to reprofile/reshape, as necessary on steel decks; (d) excellent surface texture and low requirement for PCC with high polished stone value (PSV); and (e) reduced noise due to use of smaller size PCC (in addition to the high bitumen content).

EA comprises an epoxy binder blended with crushed aggregate to provide a high quality asphalt paving product with adequate friction for the road surface. The epoxy binder has two components that, when cured, become a two-phase epoxy polymer that contains bitumen extender. The continuous phase is an acid cured epoxy and the discontinuous phase is a mixture of bituminous materials; practically, it is a thermosetting polymer.

Detailed discussions on advantages and disadvantages from the use of the EA have been explained by Widyatmoko et al. (2006; 2014) and Dinnen et al. (2020). The characteristics and main advantages for using EA surfacing as reported by several studies (Widyatmoko and Elliott, 2014; Dinnen et al. 2020; Apostolidis et al. 2020) are: (a) good waterproofing property; (b) high stability (Marshall stability in excess of 50 kN); (c) excellent resistance to deformation and fatigue cracking; (d) good load spreading ability (high stiffness, in excess of 10000 MPa at 20°C); (e) lower temperature susceptibility than PMMA or GA; and (f) good resistance to moisture and fuel damage. Nonetheless this material was also reported to have high susceptibility to workmanship issue and very sensitive to weather condition during laying operations (Widyatmoko et al. 2006).

WATERPROOFING LAYER OPTIONS

Methyl methacrylate-based waterproofing layer was recommended for use with surfacing options (1) or (2), while epoxy-based waterproofing layer was recommended for use with any option. Each surfacing system must be designed to meet performance criteria at a level deemed adequate to carry future design traffic at the bridge.

Methyl methacrylate-based material is a spray applied waterproofing membrane that has been used on large steel bridge decks worldwide. The membrane is applied in one or two layers, over the primed steel deck surface, to produce a dry film thickness between 2 mm and 2.5 mm. The adhesion of this membrane is generally sensitive to moisture; however, some proprietary systems are known to be more tolerant to moisture than others. This membrane has rapid curing characteristics (typically within an hour), therefore fast application rate and can result in seamless surface with good adhesion to substrate. Nonetheless, there are a few disadvantages from this membrane which include sensitivity to moisture (during application), being less flexible than rubberized bitumen and requires high quality bond coat to establish good bond with asphalt surfacing.

Epoxy-based waterproofing layer is typically a three component waterproofing system based on epoxy resin with refined coal tar and mineral fillers, applied 2 – 4.5mm thick (depending on traffic level). Based on the data obtained from a UK supplier, epoxy-based waterproofing system is expected to have a very high stiffness modulus of typically 2700 MPa (at ambient temperature), tensile strength of 11 N/mm^2; tensile adhesion to steel is either 2.5 or 7.35 N/mm^2 when used as bond coat or waterproofing layer respectively. The system takes between 24 and 48 hours to cure and a minimum temperature of +9°C is required to maintain the curing process. The main advantages from this system are the good waterproofing characteristics and excellent mechanical properties (high stability, rut resistant, good adhesion, high stiffness and tensile strength). However, this system must not be laid when the deck temperature is below 9^{o}C and it is not as flexible as bituminous waterproofing layer. Similar to EA surfacing, this system is sensitive to moisture during application and requires rigorous quality control on workmanship.

EFFECT OF TRAFFIC SPEED TO SHEAR MODULUS OF THE SURFACING MATERIALS

To account for the response from each surfacing option to different traffic speeds, the shear modulus value of the above materials, as shown in Figure 4, was adopted for further analysis. This value is determined by establishing a correlation between the traffic speed and the loading time of the laboratory test data, and the subsequent calculation of the mixture stiffness, based on the empirical method introduced by Van der Poel (1954) and correlated with rheological analysis as reported by Widyatmoko et al. (2002). The respective values for the materials used since the year 2001 (MA and RBU) are also displayed as reference materials.

TRAFFIC DATA

The total traffic flows from each category and each year have been counted. Data for each year and category types were divided into 365 days to provide annual average daily traffic flow (AADF). Total Annual traffic data is used to calculate the 'growth rate' between one year and the subsequent year. Of the provided traffic data, HD24/06 (Department for Transport, 2006) uses OGV1 traffic data, OGV2 and traffic data to calculate the future design traffic based on msa (millions of standard axles), i.e. in order of millions of standard 80kN axles. Note: OGV1 and OGV2 denote ordinary goods vehicle classes 1 and 2 respectively. However, for future traffic design, the super-single axle load, which is 116KN, was adopted for the design. This was decided to allow prediction of traffic damage due to the super-single axle. Passenger cars do not cause significant damage to the surfacing system and therefore were not included in the future design traffic calculations. The AADF calculated for OGV1, OGV2 and buses were 665, 285 and 11 respectively.

Past traffic and design traffic 20 years ahead (future traffic) was calculated as 4, 23 and 13.90 msa respectively. These figures resulted in the past and future traffic of 9.67 msa (which is the difference between 13.90msa and 4.23msa) and 13.90 msa respectively. Based on the super-single axle load, these values were equivalent to existing and future traffic of 2.18 and 3.14 million of 116kN axle load.

FINITE ELEMENT MODEL (FEM)

The FEM of the bridge/alignment structure was developed to assess the potential pressure on the asphalt surface at 20°C due to the influence of traffic load, to identify the key asphalt performance parameters to bring the prediction of traffic load in the future. In anticipation of different stressed modes, FEM was prepared for the main deck and cantilever. In each model, the steel deck section, the waterproofing layer and the asphalt surface were modeled to assess the impact of wheel loads. Global load impacts (e.g. wind loading) were not considered. Analysis of the deck and alignment is done using ANSYS v.11 FEM 3D. This approach allowed composite action between the deck and the MA layer. The results of this analysis were used to verify that the local behavior of the deck would not cause excess pressure on the MA surfacing.

For main and cantilever decks: transverse and longitudinal beams and troughs were modeled using a 4-noded elastic structural brick elements. Steel deck, RBU layer and asphalt surfacing were modeled using 8 noded vertices of elastic beam elements. The condition limit was applied to each model (main deck and cantilever), to simulate the confinements to the deck by the adjacent parts of the structure. The properties of the steel deck constituents were assumed to be linear, homogeneous and isotropic elastic, while its geometric properties were assumed to be non linear. Applied load was based on the super-single axle load (116 kN). The traction braking force was assumed to represent 20% of normal force and applied to one axle only, in longitudinal direction.

For each surfacing system, a total of 17 models were analyzed using the FEM analysis to estimate the maximum tensile strain within the asphalt surfacing, and the maximum shear stress and the maximum tensile stress at the interface between the surfacing and waterproofing layers, at different traffic speeds. Details were already discussed by Widyatmoko and Elliott (2013) and therefore are not reproduced here. Three surfacing systems (MA, PMMA/GA and EA), with the properties as shown in Figure 4, were subsequently considered in the analysis. These included the existing surfacing systems and proposed solutions. The results are then incorporated into the design of surfacing system, and the key findings are presented in Tables 3 to 5.

DESIGN OF THE SURFACING SYSTEM

The three main criteria considered for assessing the performance of the different surfacing systems were as follows:

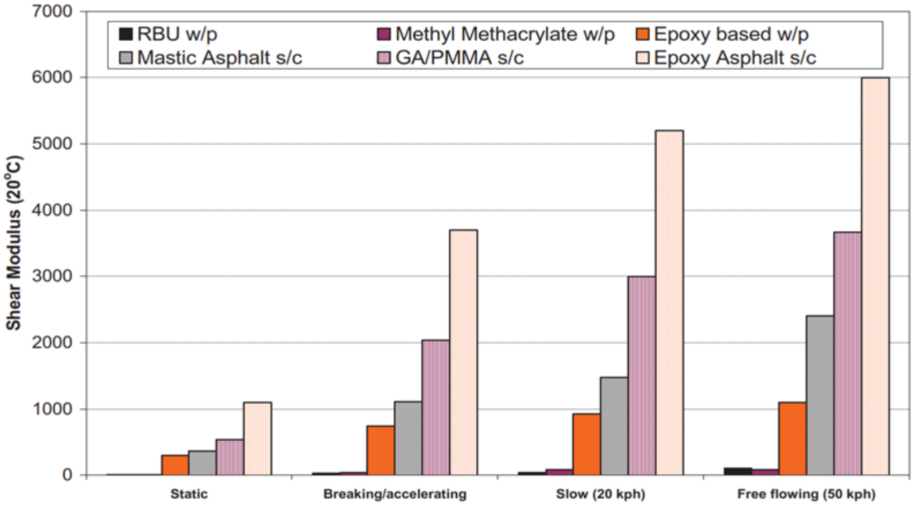


FIGURE 4. Shear modulus of surface course (S/C) and waterproofing (w/p)

1. The maximum tensile strain in asphalt surface material, to limit fatigue cracking under repeated loading.
2. The maximum shear to limit shear failures, either within surfaces that cause surface deformations, or at the interface between the surfacing and waterproofing layer.
3. The maximum vertical tensile stress, to limit the debonding between the surfacing and the waterproofing layer, and the further cracks in the surfacing.

PERMISSIBLE HORIZONTAL TENSILE STRAIN IN ASPHALT LAYER

The maximum asphalt tensile strain criterion was used to limit fatigue cracking during vehicle trafficking. The number of load applications expected during the surfacing life was used to calculate the permissible strain, which is the material fatigue characteristics. The maximum tensile strain under the 116 kN axle load that was calculated using FEM. It was then compared with the permissible strain to determine the minimum design stiffness modulus of the asphalt.

The site fatigue lines, normalized for a variety of materials, are shown in Figure 5. These lines clearly depict improved fatigue resistance from new materials (GA/PMMA and EA). These lines were derived from the laboratory fatigue test data of each ingredient. SF1 and SF2 are shift factors applied to the fatigue characteristics of each laboratory to account for material quality and different in situ conditions. This approach refers to the formula Brown et al. (1985) which has been modified for bridge deck application. Using these shift factors, 'site' fatigue lines were generated. Subsequently, the maximum permissible tensile strain at 20^{o}C was calculated using Equations (1) and (2) with inclusion of the two shift factors.

$$\log \varepsilon_{allow} = 3.07 - 0.1457 \log [N_f / (SF_1 * SF_2)] \qquad (1)$$

$$\log \varepsilon_{allow} = 3.17 - 0.1531 \log [N_f / (SF_1 * SF_2)] \qquad (2)$$

where: N_f is the accumulated traffic in 116kN standard axles; SF_1 is the shift factor to account for reduced/improved performance of asphalt surfacing (i.e. 0.5 and 2 for existing and new mastic asphalt materials respectively, and 1 for new epoxy asphalt); SF_2 is the shift factor to account for the in situ surfacing condition (i.e. 220 for existing and new asphalt materials); ε_{allow} is the permissible tensile strain (microstrain).

The permissible horizontal strain and the estimated service life for each scenario, for the main deck and cantilever lanes, are summarized in Table 3.

MAXIMUM TENSILE STRESS AT THE INTERFACE BETWEEN THE ASPHALT SURFACING AND WATERPROOFING LAYER

The maximum vertical tensile stress can cause debonding at the above interface or cracking within the asphalt surfacing or waterproofing layer. The results of the FEM analysis and their respective values expected for the existing system are summarized in Table 4.

The results show that current RBU waterproof coating material does not have adequate tensile adhesion strength (TAS), while new alternative materials show higher strength and are expected to withstand pressure caused by traffic loading. The in situ TAS testing was carried out in accordance with CD 358 (Highways England 2020).

MAXIMUM SHEAR STRESS AT THE INTERFACE BETWEEN THE ASPHALT SURFACING AND WATERPROOFING LAYER

Shear due to repetitive traffic loads can cause failure at the interface between the asphalt surfacing/waterproofing layer, between the waterproofing layer/deck, or with the waterproofing layer itself. The results of the FEM analysis and the strength values of each ingredient are summarized in Table 5.

The results show that new materials have sufficient shear adhesion strength (SAS), carried out in accordance with CD 358 (Highways England, 2020), to withstand shear stresses caused by traffic loading.

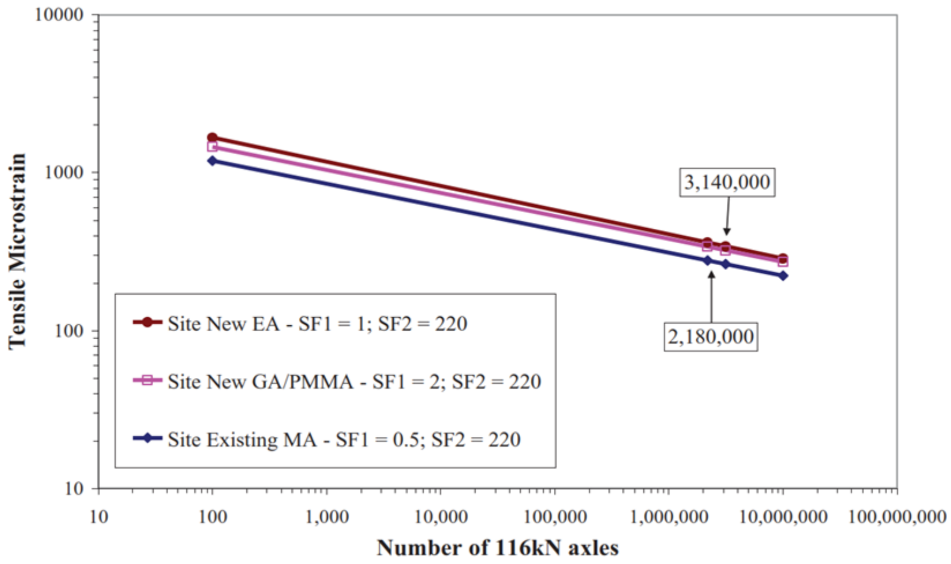
DISCUSSION

The current speed limit for vehicles crossing the road bridge is 30mph (about 50 kph). However, in reality not all vehicles run at this speed. It is therefore considered appropriate to use a conservative assumption that some vehicles will move slowly (say, 20 kph), with others might face obstacles (such as traffic jams and toll gates) or become standstill (0 kph). The following assumptions were therefore adopted in the analysis:

1. For the Northern Cantilever (NC), where traffic is dominated by non-commercial vehicles, it was assumed that the number of commercial vehicles is 30% of the total traffic;
2. For the main deck i.e. EB, CT and WB, it was assumed that the number of commercial vehicles for each line is 70% of the total traffic.

The FEM analysis results for existing surface systems show that:

1. The main deck surfacing would not be able to carry the future design traffic if the traffic speed is less than 20kph. The residual life is estimated at about 1.5 msa (or about 3 years). But if the traffic would run at speeds of more than 20kph, the material in the main deck is predicted to reach its design age;
2. The cantilever deck material will not be able to carry in the design traffic if the traffic speed is less than 20kph, with the estimated residual life of less than a year;



Note: the markers do not represent the number of test samples, but being used to identify different fatigue lines

FIGURE 5. Normalized Site Fatigue Lines for Different Surfacing Systems

TABLE 3. The predicted life for each surfacing system

Surfacing System	Traffic Speed (kph)	Horizontal Tensile Microstrain			Predicted Life (years)	
		Permissible limits	FEM Deck	FEM Cantilever	Deck	Cantilever
Existing MA	Standstill (0)	278	571	680	0.1	0.0
Existing MA	There are obstacles (0 – 20)	278	365	440	3.1	0.9
Existing MA	Free-flowing (50)	278	220	260	>20	>20
GA/PMMA	Standstill (0)	322	440	470	2.4	1.5
GA/PMMA	There are obstacles (0 – 20)	322	320	330	>20	17
GA/PMMA	Free-flowing (50)	322	175	195	>20	>20
EA	Standstill (0)	341	395	410	5.0	3.8
EA	There are obstacles (0 – 20)	341	175	235	>20	>20
EA	Free-flowing (50)	341	<100	170	>20	>20

TABLE 4. TAS and FEM maximum tensile stress

Waterproofing layer	Minimum TAS (N/mm^2)	FEM maximum tensile stress (N/mm^2)	
		Deck	Cantilever
Existing – RBU	0.95	0.92 – 1.03	4.83
New - methyl methacrylate	6.50	1.18 – 1.20	0.81 – 1.07
New – epoxy resin	2.50	1.18 – 1.20	0.81 – 1.07

TABLE 5. SAS and FEM maximum shear stress

Waterproofing layer	Minimum SAS (N/mm^2)	FEM maximum shear stress (N/mm^2)	
		Deck	Cantilever
Existing – RBU	0.70	0.27 – 0.35	0.42
New - methyl methacrylate	3.00	0.10 – 0.20	0.35 – 0.49
New – epoxy resin	2.50*	0.10 – 0.20	0.35 – 0.49

NOTE: *assumed similar to TAS.

3. In addition to the above, the risk of debonding surface of the deck is a significant negative factor in regard to the surfacing life. This was due to the TAS of the existing surfacing is either comparable with (in the case of the main deck), or less than (in the case of the cantilever deck), the maximum FEM tensile stress caused by traffic.

FEM results for alternative PMMA/GA surfacing + methyl methacrylate waterproofing system, and an alternative EA surfacing system, indicated that the main and cantilever deck materials can carry the future design traffic under moving traffic conditions (above 20 kilometers per hour).

Alternative waterproofing layers, methyl methacrylate and epoxy resin, show increased strengths (TAS and SAS) compared to the existing RBU waterproofing layer. These new materials can be expected to have sufficient strength to withstand shear and tensile stresses caused by traffic loading. Assuming new materials are manufactured and placed on strict quality control procedures, the longest service life can be achieved by the EA surface system.

RECOMMENDATION AND IMPLEMENTATION OF CONSTRUCTION

It was discussed previously that the longest service life can potentially be achieved with the EA surface system. However, it is acknowledged that there are practical problems and workmanship that need to be adequately handled if such material is successfully implemented. Furthermore, the installation cost of an EA system was estimated to be around 20 – 40% higher than that of GA/PMMA, and almost double than that of unmodified MA. As an alternative, if the traffic speed can be set to stay above 20kph, GA/PMMA can be considered to provide a more cost effective solution during the design age of 20 years.

Whichever new surfacing system is to be adopted, it is recommended that the existing material should be stripped down to the steel deck, followed by application of a new protective primer (as appropriate) prior to placing the selected new surfacing material system. As with any construction work, good quality control during installation is crucial. In this context, it is highly recommended to use machine laid system. It is noted that manual handling is more commonly adopted for installation of mastic asphalt (being self-levelling material), however this is also well known that this method will result in greater surface irregularity, and this will reduce driving comfort.

It is acknowledged that there is always the possibility of vehicle braking and traffic congestion, particularly when approaching the toll plaza. Traffic density and the creeping traffic situation will be a common challenge for these three systems. It is therefore advisable that whichever remedial option was chosen, allowance should be made in the operation and maintenance budget, to secure provision for future repair jobs.

Finally, it was concluded that the chance to achieve a 20-year design life would be higher if a thicker GA layer (e.g. 55mm or more) can be accommodated during the rehabilitation works. This suggestion was later adopted during the interim resurfacing work in 2011. The work comprised rehabilitating part of the main deck, precisely 125 linear meters ahead of the toll gates. The chosen system was the methyl methacrylate waterproofing layer and 55mm thick GA (installed in two layers). The implementation of this construction can be seen in Figure 6, where the installation of GA is done by a paving train.

PERFORMANCE MONITORING AND RECOMMENDATION FOR MAJOR REHABILITATION WORKS

Between 2011 and 2016, the field visits were routinely carried out to monitor the condition of the existing asphalt/MA (2001) and new asphalt/GA (2011). Part of the road bridges with the existing asphalt was still intact but visible signs of surface damage was getting worse. Laboratory testing (2016) in the same method as those adopted in the period 2009 – 2011, was also performed. The more recent laboratory test results provided confirmation of the deterioration in the performance of the existing asphalt. On the other hand, part of the road bridges with the new asphalt shows a much better performance than the existing asphalt. For the record, the new asphalt was located on the bridge section which receives the highest traffic load (when vehicles decelerate and stop before passing through the toll gates). This indicates that the improvement in the quality of the surfacing system has been achieved by using the new surfacing system which was recommended by Widyatmoko and Elliott (2013).

Based on the above monitoring results, three options for future major rehabilitation works have been considered, mainly by optimizing the target benefits, i.e. the funding availability and the technical considerations. These recommendations are presented as follows.

First: if the performance of the existing asphalt (MA) is considered adequate and acceptable to the road user, then it is advisable to use the same MA surfacing but with methyl methacrylate waterproofing layer. This option has the cheapest impact on the execution of work prices but is expected that routine maintenance would be required in the first 5-10 years. It is highly advisable therefore to allocate regular maintenance funds.

Secondly: if the existing asphalt (MA) performance is considered inadequate and the convenience of the road users needs to be improved, then it is advisable to adding the polymer in an MA mixture (PMMA) and use a methyl methacrylate waterproofing layer. It is also advisable to use a paving machine as this can improve the quality of the work. This option is more expensive than the first option but offers convenience for road users and can help extending the lifespan of the new surfacing and reducing routine maintenance costs.

FIGURE 6. The Implementation of rehabilitation work in 2011 at location 125 m ahead of the toll gates

Thirdly: the best option is to use the GA and methyl methacrylate waterproofing layer. The same as the system used (and tested) during the interim resurfacing work in 2011. This option is much more expensive than the other options, but it offers a longer serviceable life and can provide better quality comfort for road users.

CLOSING REMARKS

This paper presents chronologically a case study of forensic investigation of damage layer of a road bridge in England. The testing and analysis of the materials concluded decreased performance of the existing MA system. A recommendation was to replace it with stronger materials to withstand the increasing traffic loadings. In this context, an alternative material, namely GA, has been selected and used to replace the part of the road bridge, during an interim resurfacing work, precisely at a location about 125m from the toll gates. This alternative material has been monitored for 5 years and has been showing much better performance.

For the future major rehabilitation works, three alternative options have been advised to replace the current MA surfacing system, which is now deteriorating. The benefits of each of these options have also been presented to assist with decision making, in consideration of the cost and the technical side.

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DECLARATION OF COMPETING INTEREST

None.

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