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Review of Joint Repair Techniques for Thin Surface Course Systems

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1 Introduction

The work described in this report is part of the Collaborative Research Programme 2013-14. This programme of research is jointly funded by the Highways Agency (HA), the Mineral Product Association (MPA) and the Refined Bitumen Association (RBA). This review specifically relates to Sub-task 2 – Joint repair treatment of thin surfacing materials.

A previous study (McHale et al, 2011) identified that a substantial proportion of sites in Scotland with a Thin Surface Course System (TSCS) were deteriorating through severe fretting and that initiation of this fretting was often associated with the longitudinal construction joints while the remainder of the surfacing was in a satisfactory condition. Further work undertaken for the Collaborative Research Programme on sites in England recommended that a review be undertaken into the available techniques of repairing these joints, thus enabling the life span of the surfacing to be extended, without the need for complete re-surfacing.

TRL was subsequently commissioned to undertake a review and identify a range of different products, techniques and machinery that are currently available for repairing joints in TSCS. The results of the review are summarised in this report, and may be used to inform recommendations for a new clause and guidance notes in the Specification for Highway Works (SHW) 700 Series on asphalt surfacing joint repairs.

It was hoped the review would identify mechanised systems capable of carrying out consistent and rapid repairs to longitudinal joints.

1.1 Longitudinal joint construction

Ideally when laying TSCSs the pavers should lay in echelon, hence ensuring that the asphalt is hot on the both sides of the longitudinal construction joint prior to compaction. Unfortunately during maintenance this is generally not possible and hot material is laid against existing cold material on the side of the joint. This results in the rapid cooling of the adjacent material, reducing the compactibility of the asphalt at the joint, which may make this material more prone to fretting. A good example of this is a lane 1 TSCS inlay on a motorway, particularly when laid during cold winter nights. An example of a seriously fretted longitudinal joint in a TSCS is shown in Figure 1.

As part of the previous work under the Collaborative Research Programme TRL reviewed the performance of 55 sections of TSCS (between 4 and 8 years old) in three HA maintenance Areas. It was found that 73 per cent of the sections were fretting at the longitudinal joint. TRL subsequently recommended a number of changes to TSCS specifications to reduce the risk of this occurring, and also suggested reviewing methods of repairing joints.

In addition to the deterioration of the longitudinal construction joints in TSCS discussed above, the lead author has also observed an increasing number of longitudinal cracks appearing in bituminous surfacings that are reflection cracks above the construction joint in the underlying binder course. These cracks are easily identified as they appear at a nominal 300mm offset, and parallel to, the construction joint in the bituminous surfacing itself (See Figure 2).



Figure 1 Fretting at a longitudinal joint in TSCS



Figure 2 Sealed reflection type crack above a longitudinal joint in binder course

1.2 Scope of the review

The techniques reviewed included established and prototype systems, used both in the UK and internationally. These included systems that are used to backfill or repair the joint, restore skid resistance and texture, and prevent further deterioration of the surfacing.

As crack and joint repairs often use similar methods, crack repair techniques have been included in the review.

Information was gathered from published literature, manufacturers' websites and Highway Authority Product Approval Scheme (HAPAS) certificates. In addition, a number of interviews and discussions were carried out with product manufacturers and contractors using these techniques. This information was evaluated and could potentially be used as the basis for the development of a new clause in the SHW.

2 Joint/crack sealing systems

2.1 Crack sealing systems in the UK

In the UK the specification for crack sealing systems is included in SHW Series 700 Clause 711, in which both overbanding and inlaid crack sealing systems are specified. This clause has recently been supported by Interim Advice Note 158/12 where it is recommended that overbanding and inlay crack sealing can both be used to repair longitudinal joint joints.

Currently, overbanding and inlay crack sealing products need to have a British Board of Agreement (BBA) HAPAS certificate and be installed by a contractor trained in the system before they can be used on the HA network.

There are three types of crack sealing systems identified in the HAPAS guidelines document (BBA, 2010):

- (a) Simple overband systems for repairing cracks up to 5mm wide
- (b) Fill and overband systems for repairing cracks between 5mm and 40mm wide.
- (c) Inlaid systems for repairing a crack or adjacent multiple cracks (Figures 3c and 3d)

These are shown in Figure 3.

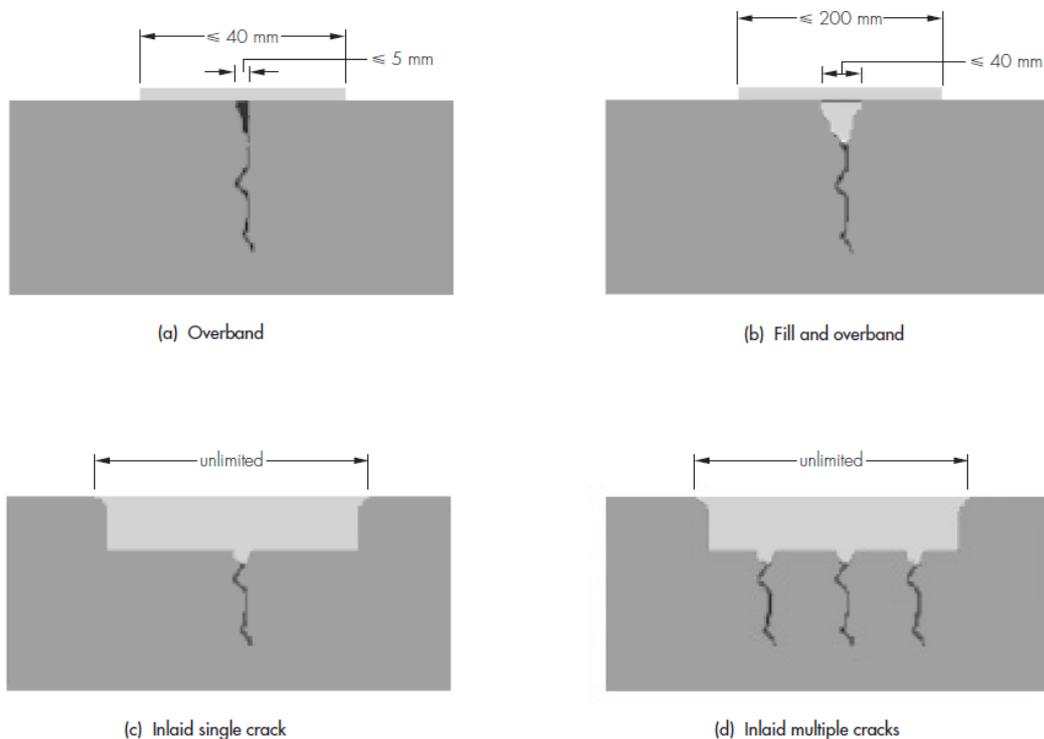


Figure 3. BBA guidelines on crack sealing (BBA, 2010)

Under present maintenance procedures it is unlikely that cracks less than 5mm wide at the longitudinal joint would be treated and therefore simple overband products are not discussed further in this document.

The BBA guidelines state that the expected service life for both fill & overband and inlay crack systems when used to seal cracks confined to the surface layers in structurally sound pavements, where the surfacing remains bonded to the base, is 5 years.

The Road Surface Treatments Association (RSTA) have recently published a Code of practice on joint repairs (RSTA, 2013), which was reviewed and endorsed by Association of Directors for Environment Economy Planning and Transport (ADEPT). This guidance is based on the DMRB, SHW and BBA guidelines

A summary of the various guidance available on crack sealing systems is given in Table 1, and it should be noted this is not always consistent. For example, the current Clause 711 only permits crack sealing systems with an overband up to 40mm wide (not 200mm as described in the BBA and RSTA guidelines). Overbanding wider than 40mm on the HA network would require a departure.

Table 1. Summary of crack sealing specifications

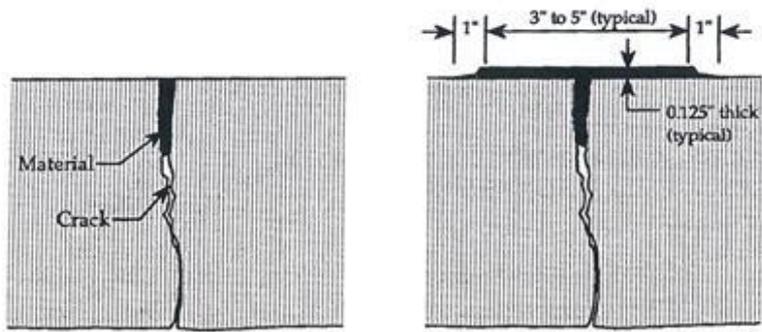
Type of sealing system	SHW Clause 711	Series 711 NG	DMRB, Vol. 7 HD31/94	BBA/HAPAS	RSTA Guide
Overband	Overband sealant must not exceed 40mm and 3mm in depth.	Cracks up to 5mm	Overband should not exceed 40mm. Sealant to be BBA accredited.	Crack up to 5mm Overband up to 40mm	Crack up to 5mm Overband up to 40mm
Fill and overband	Overband sealant must not exceed 40mm and 3mm in depth.	Cracks between 5mm and 20mm		Crack 5mm to 40mm Overband up to 200mm	Crack up to 40mm Overband up to 200mm
Inlaid		Crack > 20mm or adjacent multiple cracks		Not limited	Single or multiple cracks > 20mm Max not specified
Sealant only (Hot applied joint sealant Type N2 to BS2499-1 or BBA accredited sealant)		Narrow isolated cracks less than 20 mm in surfacings unlikely to ravel away from the crack, may be sealed without overbanding	Linear cracks without edge damage should be routed out and sealed to within 3mm of surface. Cracks needing overbanding should have overband <20mm wide	As defined in system instructions	

Note: Where not stated all dimensions refer to width.

2.2 Sealing systems in the USA

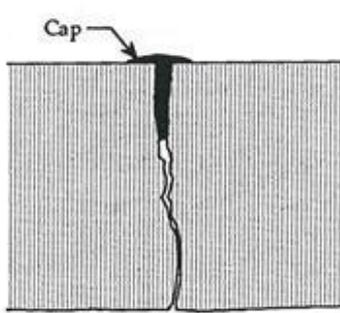
In the USA there are some variations to those systems specified in the UK. These are covered by the Federal Highway Works Administration (FHWA, 1999c) and USA National Academy of Science (1993). These are described below and shown in Figure 4.

- Flush-fill – where the crack is not milled out, it is filled and excess material removed so that the repair lies flush with surface.
- Reservoir - where the crack is milled out and then filled.
- Capped – where the crack is filled and a cap of material left on top (this produces a weaker bond, but less labour is required).
- Band-aid – the crack is filled and then overbanded.
- Recess band-aid – the crack is milled out, filled and then overbanded.
- Deep reservoir and recess – Used for deep cracks. A backer rod (polyethylene foam) is placed in the crack to control sealant depth and create a backstop, preventing three-sided adhesion. The crack is not filled to the surface, a gap is left. Backer rods are only used on straight working cracks with little edge deterioration, and are normally only used with silicone sealant.

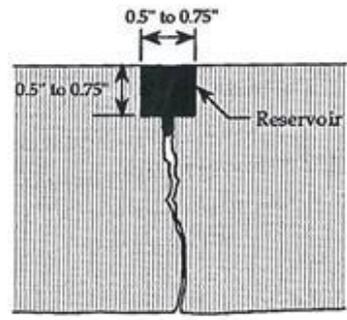


A. Flush-Fill

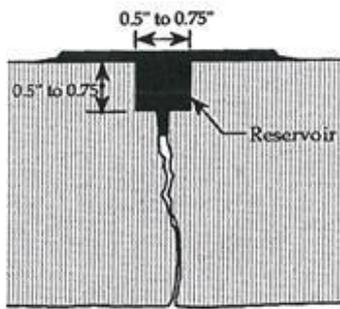
B. Simple Band-Aid



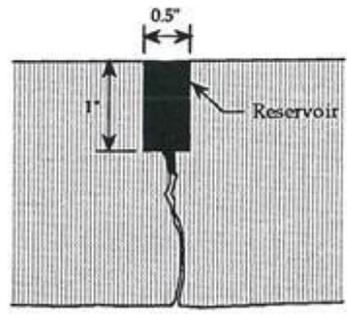
C. Capped



D. Standard Reservoir-and-Flush



E. Standard Recessed Band-Aid



F. Deep Reservoir-and-Flush

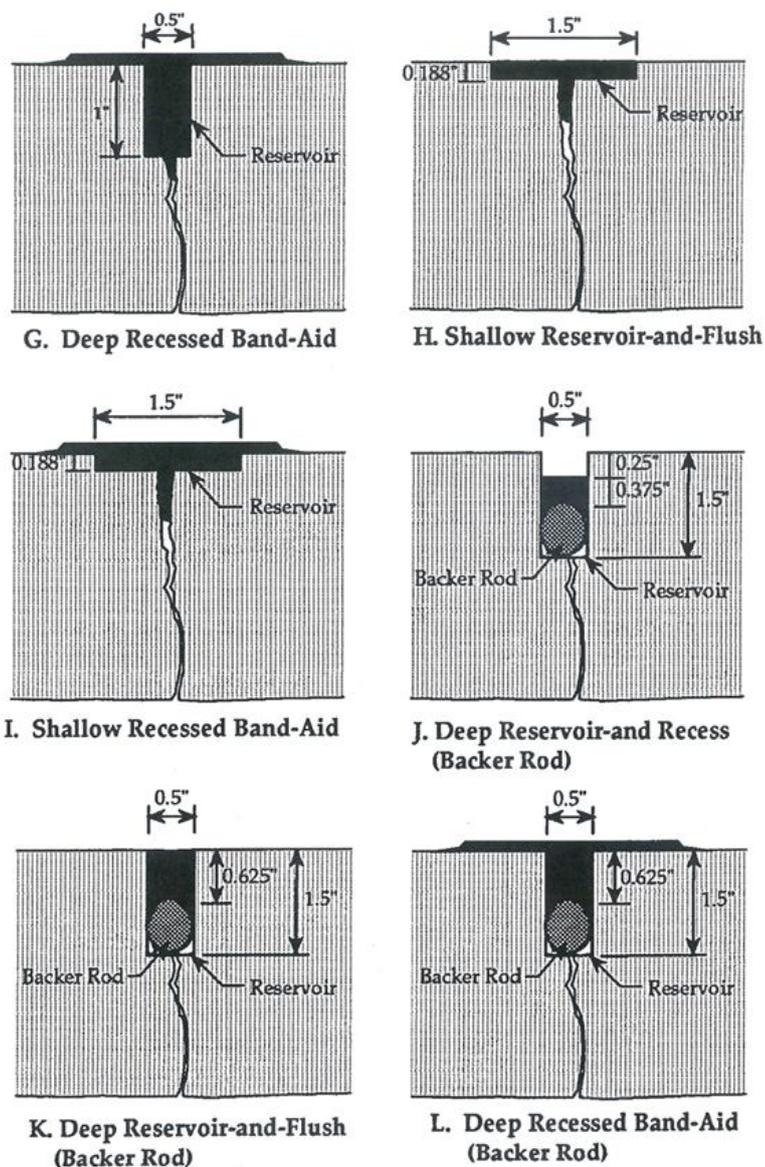


Figure 4. Material Configurations (USA National Academy of Science, 1993)

(1.0 inch = 25.4 mm)

2.2.1 Selection of the most appropriate configuration

A number of configurations and products have been trialled by the FHWA (FHWA, 1999a and 1999b). Transverse and longitudinal cracks at a number of sites across the US and Canada were treated with 31 different systems and the performance evaluated 10 times over six and a half years. The aim was to determine the most effective and economical materials and systems for treating cracks.

For Transverse cracks the most cost-effective treatments reported were the hot applied, rubber and fibre-modified asphalt materials placed in the overband and flush-fill configurations; with the majority of cracks treated being less than 6mm wide. Only one of the sites looked at longitudinal cracks, so it is unclear if the findings would apply to longitudinal joints and/or wider cracks or joints.

The FHWA study also found that the shape of the overband is important, and the optimal shape depends on the type of material used. If overband material is squeegeed flat it is referred to as a band-aid, if not it is referred to as capped. The shape factor is defined as the width/depth ratio. Rubber-modified asphalt sealants should be given a shape factor of 1 and silicone sealants a shape factor of 2. Seals with smaller shape factors are at less risk of adhesion loss.

A manual by the University of Texas (2006) recommends that active working cracks i.e. those with movement due to traffic or temperature changes, and those with large amounts of edge deterioration, should be routed before filling. Routing creates uniform edges for better adherence of the filler to the existing pavement. The manual also states that cold applied materials are less appropriate for larger cracks, and also tend to have a shorter life span than hot applied materials. The most commonly used filling configurations are flush-fill and overband. The most common configurations with routing are reservoir and combination (configurations E, G, I, and L shown in Figure 4 are combination type treatments).

2.3 Crack sealing products in the UK

There are a range of different crack sealing product types in the UK that may have been used to repair joints. These can be bituminous materials or chemically cured resins, applied cold or hot and can be one or two component systems. Adding rubber or other polymers to the mix can increase material flexibility adding more resilience to future movement. Cold laid thermoset resins normally need aggregate scattered over the repair to provide early life skid resistance, whereas hot laid thermoplastic resins and bituminous based mixes do not, as they use softer resins which wear down to expose the aggregate more quickly with trafficking.

There are a range of systems for Overbanding, Crack infill, and Inlaid crack treatments that have a HAPAS certificate; these certificates can currently be found on the BBA website (<http://www.bbacerts.co.uk/product-approval/hapas/hapas-product-sectors.aspx>).

The guidelines document for the assessment and certification of crack sealing systems for highways (BBA, 2010) specifies various grades of material. For example, Inlaid Grade F material is flexible, and is used for cracks of any size which are expected to continue to move under traffic; and Inlaid Grade H is hard material, which is used for non-active cracks. Grade F is less resistant to rutting than Grade H, but can accommodate movement. A combination can be used, for example F Grade used to fill the crack and then overlaid with a H grade when the crack is in a high stress location.

2.4 Machinery

The process of sealing a crack at a longitudinal joint involves:

- Crack cutting (optional)

- Crack cleaning and drying
- Material preparation and application
- Material finishing/shaping (optional)
- Blotting (optional) – to prevent tracking

The types of machinery that could be used for these activities are described below.

2.4.1 *Cutters or crack chasers*

There are a number of different machines available for removing the pavement around a failed joint or crack. These are referred to as cutters, routers, crack chasers, milling machines or saws. They are essentially smaller versions of a road planer. Figure 5 shows a crack chaser and a joint milling machine.



Figure 5. Crack chaser (photo courtesy of Cardinal) and Joint milling machine (photo courtesy of Schafer Technic)

There are different types of routers suited for different situations, the vertical-spindle router is more manoeuvrable, but has a low production rate. Rotary-impact routers are more productive, but can cause more damage to the pavement.

2.4.2 *Cleaners and driers*

The joint needs to be clean and dry before the filler material is applied. Debris can be removed out by hand, e.g. using a wire brush, but there are also machines which can be used for cleaning longer lengths of joint (see Figure 6).



Figure 6. Joint brushing machine (photo courtesy of Schafer Technic)

Joints can be dried using compressed air blowers or a gas burning lance (see Figure 7), again this can be by hand or fixed to a machine. Air blowers direct compressed hot air into the joint to clean and dry it; they are usually powered by propane gas. This also heats the binder in the existing pavement, improving the bond with the filler material.



Photo courtesy of Rhino Asphalt Solutions Ltd



Figure 7. Lances

2.4.3 Mixers

The cold mixes can be mixed in a bucket; a hot box (see Figure 8), kettle or boiler will be required for hot mixes. If a two part system is used, two mixers may be required.



Figure 8. Asphalt hot box (photo courtesy of Proteus).

2.4.4 Applicators

Products are often applied either by hand using a draw box (see Figure 9) or by a machine which applies the same principle (see Figure 10 and Figure 11). Depending on the product used, the new surface may need to be scattered with aggregate to provide skid resistance.

Screed (flat board) is used to smooth the repaired section. Squeegees may also be used, these consist of neoprene rubber wipers fixed to a long wooden handle used to smooth the sealant and push it into the crack. Different shapes such as V-shaped, U-shaped and straight can be purchased (see Figure 12). Vehicle mounted vibrating screeds are available, which can also be heated.



Photo courtesy of Rhino Asphalt Solutions Ltd



Figure 9. Pouring from bucket to shoe and using shoe



Figure 10. Application of infill system



Figure 11. Joint pouring lance (photo courtesy of Schafer Technic)



Figure 12. V-shaped squeegee (photo courtesy of asphalt sealcoating direct)

3 Heat and recycling systems

Heat and recycling systems are those where the pavement area to be repaired is heated then either of the following options could be used:

1. The softened area is scarified (leaving a border), any depressions topped up and levelled with fresh hot asphalt, if required, and then compacted.
2. Or the scarified material is removed from the pavement, remixed with new asphalt, and re-laid.

Both of the above treatments may also involve the use of additives.

The first technique is used mostly for patching, especially around iron work where conventional methods are more difficult. The second is used more for re-surfacing longer sections of a whole lane.

The claimed benefits of in situ heating and recycling of material include:

- More durable repairs as there are no cold joints
- Less labour is required and repairs are completed more quickly, therefore it is cheaper and less disruptive than conventional patching
- As the existing surfacing is reclaimed, there are fewer emissions and less materials are used reducing environmental impact
- Cracks don't have to be cleaned
- Improved safety for maintenance staff

Several methods of heating the asphalt surface are used. These include:

- infra-red (see Table A1 in Appendix A);
- hot air (see Table A2 in Appendix A);
- microwave (see Table A3 in Appendix A) and
- blue flame (see Table A4 in Appendix A).

3.1.1 *Infra-red heating systems*

A range of different types of equipment are available that directly heat the pavement by infra-red radiation. These are normally fuelled by propane burners and energy converters produce infra-red distributed via



Figure 13. Infra-red converters

a ceramic or steel plate or grid placed above the pavement surface and directed via steel reflectors. It takes around 5 to 12 minutes for the asphalt to soften, depending on the ambient temperature. Infra-red cannot pass through standing water, so any puddles need to be removed first. Only one pavement layer can be removed at a time.

Equipment with different sized heating plates to enable patch repairs or renewal of a whole lane is available. The heater may be fitted to a vehicle or moved into position by hand. A variety of walk-behind, fold out, truck, trailer, paver and skid-steer mounted

infrared heaters are available and some examples are shown Figure 13 and Figure 14).



Figure 14. Infra-red heater fixed to a tractor

In some techniques the heaters form part of an equipment train consisting of a number of heaters, re-mixer, roller etc. This has been used in Japan and the USA for full lane width rehabilitation (see Figure 15).



Figure 15. Hot in-place recycling (Hosokawa et al, 2005)

There are also machines which combine heating and reclaiming equipment (see Figure 16).

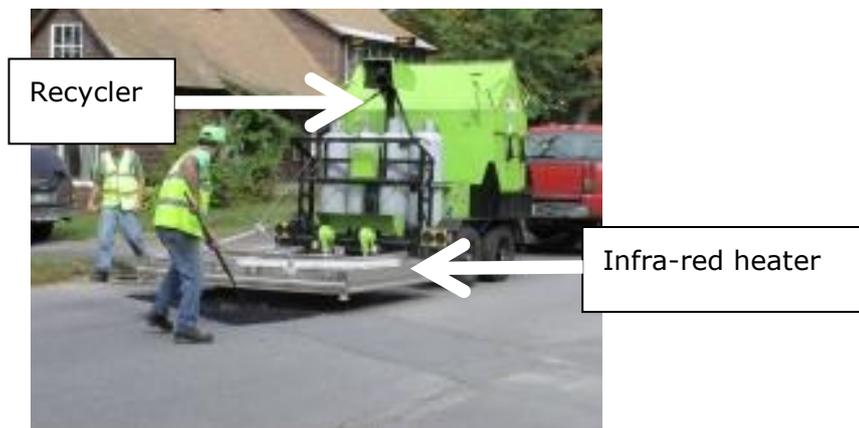


Figure 16. Combined infra-red heater and reclaimer on a trailer (photo courtesy of Ray-Tech Infra-red, 2013)

There are specialised infra-red heating systems designed specifically for joints. These are normally used to heat the edge of an existing pavement before the adjacent lane is resurfaced to mitigate the effect of cold joints between lanes. These usually comprise a series of long thin infra-red heaters linked together and towed by a truck as shown in Figure 17. A paving rate of 35 feet (10.7m) per minute is claimed.



Figure 17. Large infra-red joint heater



Figure 18. Smaller infra-red joint heater

There are a few manufacturers who mention using either joint heaters or other IR heaters to repair longitudinal joints.

In the UK, it is possible to hire-out infra-red heaters for both pothole and joint repair. This process includes heating of the existing asphalt, adding new approved materials prior to manual mixing as required, and compaction. An example of this type of procedure is shown in Figure 19.



Figure 19. Joint repair procedure (photo courtesy of Nuphalt)

A similar system set up specifically for joint maintenance is shown in Figure 20.

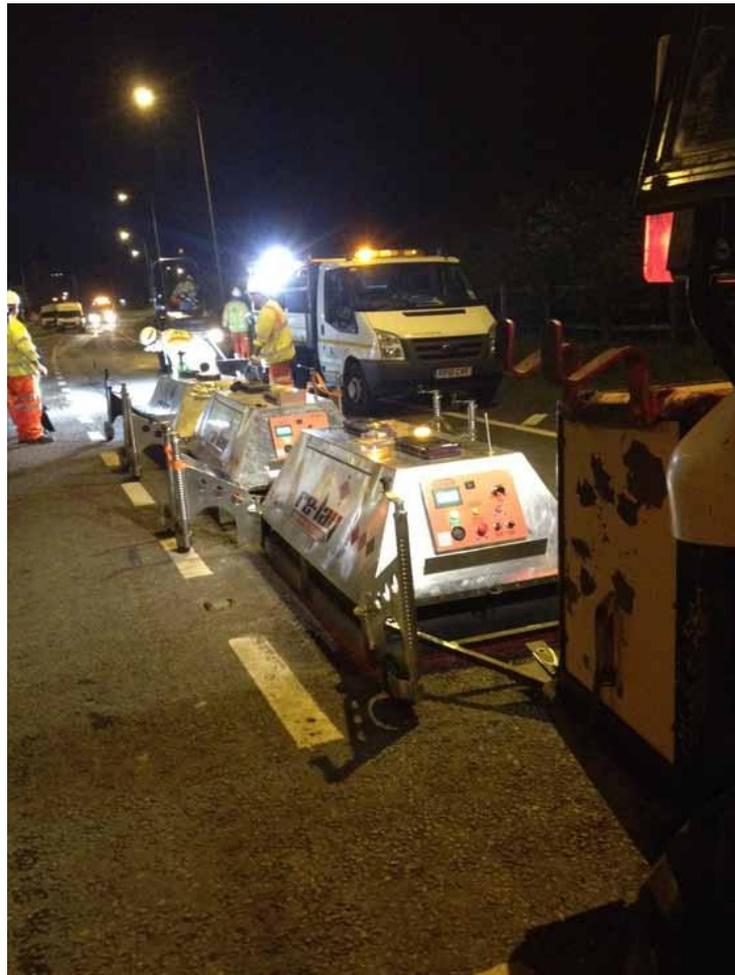


Figure 20. Infra-red heater units set up for joint repair (photo courtesy of Re-Lay Asphalt Services)

In its current form the Relay system still requires manual scarification and rejuvenation prior to compaction. However TRL understand that a prototype machine that will combine heating, scarification and rejuvenation is under development (see Figure 21).

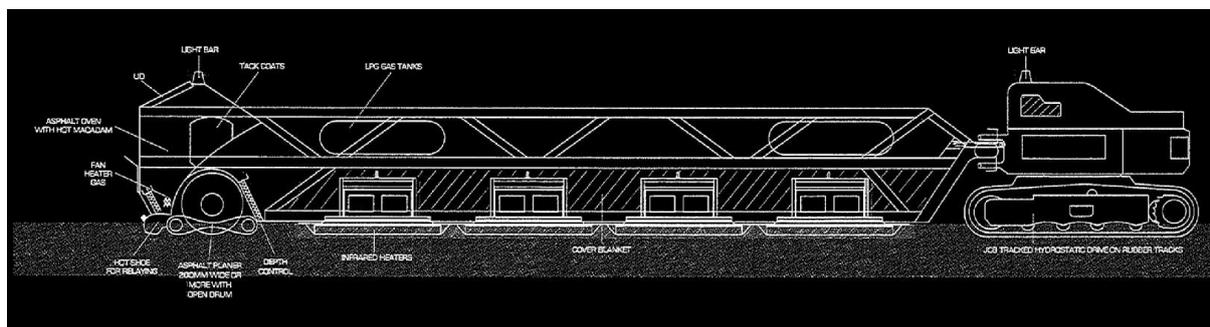


Figure 21. Prototype joint repair machine

A company in Germany has developed an automated joint repair system that utilises multiple infra-red heaters. The system, shown in Figure 22, heats the surfacing adjacent to the joint to 190°C and recycles the material with new asphalt material/rejuvenator. The joint is then compacted and high PSV aggregate added if needed. With the set-up shown in Figure 22 it is claimed to have an output of 2m/min.



Figure 22. Infra-red heat and recycling system (photo courtesy of ASI)

A Canadian manufacturer has used a joint heater (see Figure 23) to repair ravelled joints in Canada and the USA (including outside the White House). The joint was heated and additional asphalt from a mini-recycler used to fill the voids.

A hot in-situ joint repair scarification unit which combines the joint heater and a scarifier is being developed. They claim it 'rebuilds' joints at 5 feet per minute using a train of heaters which are followed by a scarifier. Rejuvenator is sprayed on using a pump and nozzle assembly, sand mix is added, then a specially constructed adjustable spreader box levels and pre-compacts the material. The repair is finally hand prepared and then compacted with a vibratory roller. They are developing this process to produce rates of 10 feet per minute.



Figure 23. Joint heater (photo courtesy of Heat Design Equipment Inc.)

Examples of available infra-red equipment are given in Table A3 in Appendix A.

3.1.2 Hot air heating

Although less common there are some types of heaters which use convection to heat the pavement, blowing hot air onto the surface (Figure 24). Some research suggests that using hot air heating is more uniform and effective than heating by infra-red (Mallick *et al*, 1997).



Figure 24. Heating using hot air

In this process propane gas is used to heat air, which is blown onto the road surface through a series of nozzles. The air is collected and recirculated.

3.1.3 Microwave heating

The heating of asphalt using microwaves is less established than infra-red heating although it is reported to have several advantages. Asphalt has low thermal conductivity, so surface heating via infra-red or hot air does not penetrate very far into the pavement, typically up to 50mm. It is claimed that microwaves enables further penetration into the pavement and that they can be used to repair deep cracks up to 180mm depth. It also heats more uniformly, rather than from the top down. The microwaves heat up the aggregate, which warms the binder without over heating it. The heating unit (powered by diesel) seals to the ground, so no radiation escapes. The units can be vehicle or trailer mounted (as shown in Figure 25).



Figure 25 Trailer mounted microwave unit (photo courtesy of New Timehope)

There are some studies which trialled the addition of aggregate containing iron minerals (e.g. taconite) to the repair mixture (Construction News, 2012). This increases the heating rate and enables the heat to penetrate further into the pavement. The aim of the

study was to produce a technique that would enable patch repairs to be carried out during the winter, when the ground is frozen.

3.1.4 Blue flame heating

In this technique a rolling blue flame is applied to the asphalt surface to pre-heat joints. The blue flame produced by burning LPG heats the pavement through radiant heating. There are some concerns that the flames can damage the asphalt surface and/or only heat the surface. An example of a blue flame heater designed for long cracks or joint repair is shown in Figure 26. The manufacturer claims that this can heat to a depth of 70mm.



Figure 26. Folding blue flame joint sealer (photo courtesy of Reed, 2014)

4 Discussion

The prevalence of deterioration in TSCS starting at joints has been noted in studies in Scotland and previous work under the collaborative research programme; the findings effectively led to this study. The treatment of any deterioration is therefore important if TSCSs are to reach their expected service lives of 13 years reported by the TRL study (Nicholls *et al*, 2010).

The need for joint sealing and/or repair may therefore increase in line with the increased use of TSCSs on the HA network. This reason for this is that TSCSs are not particularly tolerant to variability in construction practice nor do they lend themselves to road maintenance constraints on the HA network, such as night working and single lane inlays which effectively have two 'cold' longitudinal joints.

This 'intolerance' was evidenced by significant joint deterioration noted under the previous studies.

The cost of any maintenance technique must be kept to a minimum to enable it to provide value for money. For example, if a longitudinal joint is to be treated part way through the life of a surfacing, the treatment should be required to last for the remaining expected life of the TSCS and/or whole pavement. That is, a long-lasting and expensive treatment may not necessarily provide value for money to the tax-payer as it could potentially out-last the bulk of the material in the mat.

The most effective method of preventing the premature fretting of the construction joint in TSCS is to ensure they are initially well constructed. Where possible thin surfacing systems should be laid in echelon to ensure the material on both sides of the longitudinal joint is hot, and adequately compacted. Where this is not possible 'cold' joints should be heated and painted at the same time as described in Road Note 42 (Nicholls *et al*, 2008).

If the material at the longitudinal joint starts to fret coarse aggregate from the matrix during service, the most appropriate maintenance technique is likely to be the application of a proprietary 'fill and overband' system prior to the joint getting wider than 40mm.

If maintenance of the longitudinal joint is delayed and the joint width is consistently greater than 40mm, then an appropriate 'heat and recycling' system could be an effective maintenance solution, providing the adjacent mat has an appropriate amount of residual life that is comparable with the maintenance treatment. To date, there has been limited use of 'heat and recycling' systems in the UK for joint repair as the majority of the available equipment has been developed for pothole type repairs and the equipment has to be manually manoeuvred into position and then can only be used to heat relatively small areas at any one time.

Ideally for this type of system to present good value for money, the equipment needs to be automated and vehicle mounted enabling a speedier, consistent, operation suitable for greater lengths of longitudinal joints. At present there is only one known system like this that could be made available for use in the UK, although there is the desire to develop similar equipment by a UK manufacturer.

Besides fretting at the longitudinal joint, maintenance repairs using heat and recycling systems may also be appropriate at failures under road markings (Figure 27) and TSCS where roadmarkings have previously been burnt off (Figure 28).

The use of 'heat and recycled' systems could also be beneficial during the construction phase to 're-work' open, cold or uneven joints thus avoiding remedial works or early intervention maintenance, and may be particularly applicable to inlay maintenance.



Figure 27 TSCS 'white line' failures – HA Areas 12 and 10 respectively



Figure 28 TSCS fretting as a result of 'burning off' road markings - HA Area 10

5 Next steps

The Steering Committee has agreed, in principle, that a proposed demonstration trial of the German heat and recycling system (Figure 22), available through ASI Solutions, should be undertaken on the HA network. The trial should ideally be TSCS to TSCS and should assess the logistics of the process, the speed of operation, and the quality of the finished surface after completion. The trial itself would be paid for as part of the scheme maintenance and is beyond the scope of this project.

6 Acknowledgements

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Appendix A Examples of products and equipment

Table A1. Examples of infra-red pavement heaters

Type	Description	Application	Reference
Infrared Combination Reclaimer & Pavement Heater	An infra-red heater and reclaimer to heat/store new and reclaimed asphalt mounted on a trailer. Requires two staff to operate.	Patching.	http://www.raytechinfrared.com/sites/default/files/MC-C%20Brochure.pdf
Infrared Asphalt Joint Heating System	A series of long thin infra-red heaters that are designed to seal joints.	To pre-heat joint edges before new surfacing is laid.	http://www.raytechinfrared.com/sites/default/files/JH%20Brochure.pdf
HDE JMH (Heat Design Equipment)	An infra-red joint heater mounted on a trailer. Powered by propane, it heats ceramic plates which are placed over the road surface.	Failed joints.	http://www.asphaltheater.com/products/joint-match-heaters/
IRMAC AR2 infra-red asphalt heater	Infra-red heater which is used in the UK. Runs on LPG and re-chargeable solar battery. Rate of 60 sqms per day per two man team.	Joint failures, trench reinstatements, defects around ironworks and potholes.	http://www.irmac.co.uk/wp-content/themes/shades-of-blue/brochure/Irmac-E-Brochure.pdf
Wirtgen HM 4500 Preheater	M 4500 Preheater and the RX 4500 Remixer used in China. IR heater softens asphalt, which is scarified with remixer and transferred into remixer where additional asphalt and rejuvenator is added. The integrated paving screed relays the asphalt, which is then compacted by a following roller. 3000m ² per 7 hour	Patching lanes (4m)	http://www.wirtgen.de/media/redaktion/pdf-dokumente/04_heissrecycling/remixer_4500/jr_remixer_china/jr_remixer_4500_china_e.pdf

	day (1.6 m to 2.2 m per minute).		
ASI Solutions Ltd	Infra-red heater systems.	Various systems available. Static heater system available for patching. Automated heating/scarifying/rejuvenating system available for joint repair.	http://www.youtube.com/watch?v=RCYeHyN1u8I&feature=youtu.be
ECOSeam	A Dutch joint IR heater.	Joining new surfacing to old.	http://www.bobema.com/PDF/Joint%20Heaters/EcoSeam.pdf
KASI Infrared	A range of IR heaters from Hungary including smaller versions that are moved by hand or truck or trailer mounted heaters. There is also a seam heater and a heater combined with recycler and compacter on one chassis.	Potholes, surface cracking, reinstatements, trenches and paver seams. Suggests 2 or 3 person crew.	http://kasiinfrared.eu/en/
nu-phalt	'Thermal road repair system' with BBA HAPAS. Recommended not used below freezing or in heavy rainfall. IR heater and other equipment on one vehicle. Two people to operate. Includes a Joint Failure Heater (2 x 0.5 m ²).	Potholes, trench surface repairs, reinstatement of failed joints and seams.	http://nuphalt.com/
B-Pothole-FREE	A US infra-red system.	Potholes	http://www.bpotholefree.com/
AshPave	Australian infra-red heater.	Patches, potholes, 'ugly joints' and cracking.	http://www.ashpave.com.au/infrared-asphalt-repair.html

Table A2. Examples of hot air pavement heaters

Name	Description	Application	Reference
Re-HEAT (Angelo Benedetti)	A machine which heats, scarifies, adds rejuvenator and relays.	Lane re-surfacing	http://angelobenedetti.com/re-heat.php
Truck-mounted hot recycler	A machine that heats, then reclaims and relays the surface. Also has a roller.	Repair of potholes and cracks	http://en.assyrb.com/products/ad5140trxrefengshizaishengxiubuche.htm
Senyuan hot recycler	It can heat, scarify, additive spray (reclaiming agent, new asphalt, mix agent etc.), add new asphalt mixture and relay.	Repair of large areas of pavement.	http://en.assyrb.com/products/lumianliqing.htm
AR2000 Super Recycler	A Japanese pavement heater using hot air. Consists of an equipment train of heaters, miller, paver and roller.	Surface repair of whole lane. Equipment is long (45m) and wide. Shouldn't be used below 10°C or when raining. Construction rate 1.5 to 15 m/min. Claims to be more environmentally friendly than IR heaters, although noise and fumes are mentioned (especially if there is crack sealant) by FHWA. They recommend the scarification process is only used on low volume roads.	http://www.green-arm.com/e/ar2000/flow/index.html and http://www.cflhd.gov/programs/techDevelopment/pavement/context-roadway-surfacing/documents/context5-append-a8.pdf

Table A3. Examples of microwave pavement heaters

Name	Description	Application	Reference
EAGER series Microwave Recycling Maintenance Vehicles (Reed)	A microwave heating system (Chinese). Heats 6 to 18cm deep.	Patching.	http://www.veeya.com/English/Product.asp?ID=121

Table A4. Examples of blue flame pavement heaters

Name	Description	Application	Reference
Asphalt seam heater (Asphalt reheat systems)	Heater panels which fit to a trailer. A rolling blue flame is used to heat the pavement.	Reheating cold paving joints, stamping extended borders, blending uneven seams	http://www.asphalthereheat.com/ARS_SEAMHEATER_INFO.pdf and http://www.forconstructionpros.com/product/10831743/asphalt-reheat-systems-manta-ray-asphalt-heater-trailer
EAGER series Folding Blue-ray Asphalt Recycling Machine	A blue-ray thermal radiation pavement heater that folds for ease of transportation.	Long crack and joint repair.	http://www.veeya.com/English/Product.asp?id=136
Esund	Japanese blue flame heater.	Potholes, alligator cracks, high spots, tire dents, spalling joints	http://www.esungd.com/html/products-50.html