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APPLICATION OF BRIDGE DECK WATERPROOFING TO CONCRETE AGED FROM 3 TO 28 DAYS

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Executive Summary

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Project Reference:	Contract 3/359 – Task 37: Bridge deck waterproofing – early application
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Scope of the project

Highways Agency (HA) requirements relating to bridge deck waterproofing are contained in Departmental Standard BD 47/99 (Highways Agency et al, 1999). Waterproofing systems that have satisfied the requirements of the certification tests that are specified in the Standard are considered suitable for use on bridge decks where the concrete age is 28 days or more. Therefore, currently, waterproofing is normally applied a minimum of 28 days after decks are cast. This delay may increase congestion on the road network, so TRL was commissioned by HA to determine if it would be possible to decrease the age at which concrete bridge decks can be waterproofed.

A literature review was carried out to determine how the performance of waterproofing systems may be affected when applied to concrete less than 28 days old. A series of tests was then carried out on the four waterproofing systems that are registered by the BBA and have Roads and Bridges Agrément Certificates, using the 'standard' primers specified in the Certificates, and a system approved for use in Germany. These systems, referred to as Systems 1 to 5, were applied to concrete slabs manufactured from four mixtures aged from 3 to 28 days. This report describes the outcome of the tests and makes recommendations concerning the application of waterproofing systems to concrete aged less than 28 days.

Summary

Three spray applied systems (Systems 1 to 3), one pour-and-roll sheet system (System 4) and one torch-on sheet system (System 5) were applied to test slabs measuring 300mm square by 55mm deep. The slabs were manufactured from the following concrete mixtures:

- a gravel aggregate concrete with ordinary cement (CEM1)
- a gravel aggregate concrete with ground granulated blastfurnace slag as a partial cement replacement (CEM1/GGBS)
- a lightweight aggregate concrete including Lytag with CEM1 (Lytag)
- a typical cementitious repair material within a recess in a CEM1 concrete slab.

For each system, a total of 48 slabs were waterproofed when they were aged 3 days, 7 days, 14 days or 28 days. The 3-day slabs were cured under wet hessian for 3 days. The other slabs were cured under wet hessian for 7 days and then left to dry. Half of the 14-day and 28-day slabs were immersed in water for 60 hours and removed from the water and left to dry in air on the morning of the day they were waterproofed. The waterproofing systems were not applied before the surfaces were deemed by the approved applicators to be sufficiently dry. The surface moisture content of the System 2 slabs was measured using a moisture meter, whereas the other slabs were assessed visually. The slabs were flame dried to achieve the appropriate surface condition. More drying was required for System 2 than for the other systems.

Two days after waterproofing, the membrane was covered with hot sand to replicate the high temperatures encountered during the application of road surfacing material. Tensile adhesion tests were performed on the slabs from 28 days after they were waterproofed to determine the strength of the bond of the waterproofing system to the concrete. The tests were carried out at three temperatures; -10±2°C, 23±2°C and 40±2°C.

The following conclusions were drawn from the work:

1. The time required to apply the five waterproofing systems to the slabs varied greatly. The spray applied systems were applied within a few hours, whereas the time required to cure the primers of the sheet systems delayed the installation of their membranes.
2. The waterproofing systems were not applied before the surfaces were deemed by the applicators to be sufficiently dry. The surface moisture content of the System 2 slabs was measured using a moisture meter, whereas the other slabs were assessed visually. The slabs were flame dried to achieve the appropriate surface condition. More drying was required for System 2 than for the other systems.
3. No pin/blow holes or blisters were evident on any of the slabs of any system at any stage throughout the test programme.
4. At a test temperature of -10ºC, the tensile adhesion of all five systems exceeded the minimum specified in BD 47 (0.3MPa) by a considerable margin.
5. At a test temperature of 23ºC, the tensile adhesion of the spray applied systems exceeded the minimum specified in BD 47 (0.3MPa) - by a considerable margin for System 1 and for all but one or two tests for Systems 2 and 3. The tensile adhesion of the sheet systems generally exceeded the minimum specified in BD 47 for the CEM1 and CEM1/GGBS slabs, and for the repair slabs for System 5. Some values below the minimum were measured on the Lytag slabs and on the repair slabs for System 4.
6. At a test temperature of 40ºC, the tensile adhesion of the spray applied systems exceeded the minimum specified in BD 47 (0.2MPa) by a considerable margin, but the tensile adhesion of the sheet systems was mainly below the minimum specified.
7. The tensile adhesion was different for the different substrates. The substrate which gave the highest tensile adhesion varied with the system, the test temperature and the age and curing regime. For most systems and test temperatures, the tensile adhesion varied little with the age and curing regime of the slabs. Some lower tensile adhesion values were measured on some of the 3-day slabs and wet slabs for some systems.
8. Higher tensile adhesion values may have been measured if System 4 had been overlaid with surfacing that had been rolled, and if System 5 had been overlaid with Güssasphalt at 240ºC - an integral part of this system in Germany.
9. Generally, the findings from these tests were consistent with the findings from other studies.
10. Taking all factors into account, it is concluded that the performance of waterproofing systems on bridges should not be adversely affected by application to concrete aged 7 days or more, provided they are applied in the same way as during the tests reported here. In particular, the time between surface drying and the application of the primer should be as short as possible so that any moisture that may migrate from the bulk of the concrete material back to the surface is minimal.
11. Pull-off tests should be conducted on site after the installation of the membrane and before surfacing to confirm that the condition and dryness of the surface of the concrete was sufficient to give adequate initial tensile adhesion of the waterproofing system to the concrete.

Abstract

Highways Agency (HA) requirements relating to bridge deck waterproofing are contained in Departmental Standard BD 47/99. Waterproofing systems that have satisfied the requirements of the certification tests that are specified in the Standard are considered suitable for use on bridge decks where the concrete age is 28 days or more. To determine if waterproofing systems can perform satisfactorily when applied to younger concrete, a series of tests was carried out on the four waterproofing systems that are currently registered by the BBA and have Roads and Bridges Agrément Certificates, using the 'standard' primers specified in the Certificates, and a system approved for use in Germany. The systems were applied to concrete slabs manufactured from four mixtures aged from 3 to 28 days that had been subjected to different curing regimes. The slabs were waterproofed by the suppliers of the systems after they were surface dried in accordance with normal site practice, as deemed necessary by the suppliers. The day after the application of the systems, the slabs were overlaid with hot sand to simulate the high temperatures encountered during surfacing. Observations were made for blisters and tensile adhesion tests were carried out at -10^{o}C, 23^{o}C and 40^{o}C from 28 days after waterproofing. It was concluded that the performance of waterproofing systems on bridges should not be adversely affected by application to concrete aged 7 days or more, provided they are applied in the same way as during the tests. In particular, the time between surface drying and the application of the primer should be as short as possible so that any moisture that may migrate from the bulk of the concrete material back to the surface is minimal. The findings from these tests were consistent with other research.

1 Introduction

Highways Agency (HA) requirements relating to bridge deck waterproofing are contained in Departmental Standard BD 47/99 (Highways Agency et al, 1999). Waterproofing systems that have satisfied the requirements of the certification tests that are specified in the Standard are considered suitable for use on bridge decks where the concrete is aged 28 days or more. Therefore, currently, waterproofing is normally applied a minimum of 28 days after decks are cast. This delay may increase congestion on the road network, so any decrease in the age at which concrete can be waterproofed would be beneficial. TRL was commissioned by HA to determine if this would be possible by carrying out tests on four waterproofing systems that are registered by the BBA and have a Roads and Bridges Agrément Certificate, and a system approved for use in Germany. These systems, referred to as Systems 1 to 5, were applied to concrete slabs manufactured from four mixtures aged from 3 to 28 days, and their performance was compared.

When waterproofing concrete less than 28 days old, suppliers sometimes use a different primer to the ‘standard’ primer specified in the Roads and Bridges Agrément Certificate. However, for these tests only ‘standard’ primers were used.

2 Background

The most significant differences in the performance of a waterproofing system applied to 28-day old and younger concrete are likely to be dependent on:

- the resistance to blow/pin holing and blistering of the system,
- the bond of the system to the concrete,
- the effect of the moisture content of the concrete on the curing of components of the system, and
- shrinkage and load induced cracking.

These factors are dependent on:

- the type of concrete
- the surface finish of the concrete
- the moisture content of the concrete when the waterproofing system is applied
- the temperature of the concrete when the waterproofing system is applied
- the type of the waterproofing system, in particular the type of primer
- the temperature history after the waterproofing system has been applied, including the temperature of surfacing materials

Pin/blow holes and blisters are formed by out-gassing when air, water vapour or solvents in primers within voids in concrete are expelled due to changes in temperature or, sometimes, barometric pressure. Pin/blow holes are formed only when liquid-applied systems are curing – the longer it takes for them to cure, the greater the likelihood that they will form. Blisters may form any time after installation. Out-gassing is most likely to occur when the temperature of a deck changes rapidly due to solar radiation or due to the application of hot surfacing materials. As concrete ages, the size of the pores decreases, therefore concrete aged less than 28 days may be more prone to out-gassing than older concrete.

The initial bond of most waterproofing systems to concrete is dependent on the surface moisture content of the concrete during waterproofing. The bond strength will be reduced if surface moisture is present, especially if it impairs the curing of liquid applied components. Over time, even if out-gassing does not form blisters, it may weaken the bond of the system to the concrete. The bond may also change as the concrete ages and cures.

A waterproofing system should remain uniformly bonded to a concrete deck throughout its service life. Almost all membranes can have small defects through which chloride ions can pass. If the membrane is firmly bonded to the concrete, the number of chloride ions that can pass through a defect is normally low and the ions can reach only a small area of the deck. However, if a membrane has a defect where it is not bonded to the deck, many chloride ions can pass through the membrane and the likelihood that they penetrate the concrete and cause reinforcement corrosion is much higher.

Shrinkage and load induced cracking may be significant in the hogged regions of continuous multi-span decks. A waterproofing membrane and its overlaying surfacing may be subjected to larger tensile strains if they are applied to a deck before the onset of cracking.

3 Literature review

A literature review was carried out to identify research to determine the factors that effect the formation of pin/blow holes and blisters in waterproofing systems and their adhesion to concretes of different type aged 28 days or less.

Price (1995) describes tests to determine the nature of pin/blow holes. Concrete slabs were cast and kept under controlled conditions generally at a temperature of 5 to 7ºC and relative humidity from 80 to 90%. The concrete was grade C40 with ordinary Portland cement (OPC) and nominal mix proportions 1:2:3.5 for cement:sand:aggregate, but lean mix areas were created in the slabs.

The slabs were left to dry naturally and, although the surfaces dried, resistivity measurements showed that the moisture conditions within the slabs did not stabilise until the concrete was 10 to 12 weeks old. Therefore, it was considered that there may be sufficient moisture to cause blistering and pin holing for some time after the surface appeared to be dry.

The surfaces were wire brushed to remove laitance before four waterproofing systems were applied, including a spray applied system and a pour-and-roll sheet system. In general, the surfaces of the slabs were dry enough to apply the waterproofing systems after 14-17 days. Water was applied to some slabs after 24 hours to simulate rain (for a period of 2 hours) and their surfaces were 21 days old before they were dry enough to apply systems. There was no artificial drying. Some areas were not primed and in other areas the primer was applied poorly or to a wet substrate.

For the spray applied system, there was no correlation between the lean mix areas and the pin holes. However, there was significant correlation between the pin holes and the moisture content, and between the primed and unprimed areas. Most pinholes occurred in unprimed areas with a high moisture content.

Brocklesby et al (1994, 1995a) describes tests to determine the effects on moisture and surface drying on the integrity of waterproofing systems. The tests were carried out on 300mm and 450mm square slabs of depth 100mm manufactured from C40 concrete with OPC, OPC with pulverised fuel ash (PFA), and OPC with ground granulated blastfurnace slag (GGBS). The results obtained from measurements of moisture content by proprietary devices were compared with gravimetric measurements on dust samples from drilling after the slabs had been subjected to different periods of wetting and drying to produce different moisture contents and moisture profiles within the slabs. The effects of surface drying with a flame and thermal lance were investigated. Seven waterproofing systems, including two spray applied systems, one pour-and-roll sheet system and one torch-on sheet system, were applied to the slabs of different moisture content and age ranging from 7 to 28 days. The surfaces of the slabs were allowed to dry naturally or artificially before the application.

Pull-off tests were carried out within 7 days of the application of the waterproofing system and again after 6 months. There was no clear relationship between the tensile adhesion strength at 7 days and 6 months and the bulk moisture content of the surface dried slabs. The variation in the adhesion between the waterproofing systems was markedly greater than the variation with the bulk moisture content.

The causes and effects of out-gassing were studied by Chadwick and Bamforth (1992). The rate of flow of gas from an exposed concrete surface is dependent on the permeability of the concrete, the pressure in the heated zone and atmospheric pressure. If the gas is confined by a waterproofing membrane, the pressure beneath the membrane may increase. Solar radiation can cause an increase in surface temperature to as high as 75ºC. This may increase the pressure beneath a membrane by 0.02 to 0.03MPa, so it was considered that blistering is unlikely to occur due to solar radiation unless a waterproofing system is poorly bonded to the concrete. To generate a pressure of 0.3MPa would require a temperature increase at the concrete of the order of 115ºC (e.g. from 20ºC to 135ºC). It was concluded that such a temperature increase could arise when the waterproofing system is overlaid with hot asphalt.

BD 47/99 requires tensile adhesion strengths to be a minimum of 0.2MPa at 40ºC. The tensile adhesion of most waterproofing systems decreases with temperature. Although the adhesion may not fall to as low as 0.03MPa at 75ºC, the authors of this report believe it could be significantly lower than the 0.3MPa referred to by Chadwick and Bamforth at the high temperatures encountered during surfacing. Therefore, blistering could occur during surfacing and, even if it does not, the adhesion could be weakened.

Brocklesby et al (1995b) carried out tests to determine the effect of factors that could influence out-gassing, including concrete mix type, curing period, surface finish and treatment, and the moisture content of the concrete. The moisture content was the most significant factor. Provided the surface was dry, there was less out-gassing for concrete mixtures with higher the bulk moisture contents because, it was concluded that the volume of air filled pores and air permeability of concrete reduces as the moisture content increases. The application of hot surfacing materials was not considered in the tests.

C40 grade concrete produced less out-gassing than C20 and C10, and there was less out-gassing as the curing time prior to waterproofing increased. The addition of PFA did not affect the rate of out-gassing of C40 grade concrete. GGBS produced in-gassing, but the reason for this was not known. Flame drying of the concrete surface tended to reduce out-gassing because it preheated the concrete and there was partial cooling when the waterproofing system was applied. The use of primers containing solvents gave out-gassing which was orders of magnitude greater than that resulting from temperature change.

Two spray applied waterproofing systems were applied to slabs of C40 grade concrete with a concrete age of 28 days and had been subjected to different curing regimes. The slabs were cooled to 6ºC for the application of the primer and then placed on a water bath at 25ºC. The membrane was applied to some slabs immediately after they had been removed from the cooler, and to others after a 10 or 20 minute delay. It was found that the bulk moisture content should be greater than 4.5% to reduce the risk pin holing, but the surface should be dry to ensure adequate bond and avoid blistering. Blistering appeared to be associated with very wet surfaces, even when the out-gassing rate was low.

Stevenson and Evans (1991) carried out adhesion tests on four types of C40 grade concrete, including concrete with air entrainment, PFA and GGBS. Waterproofing systems were applied to slabs aged from 7 days to one year. For the sheet systems, there was no effect of concrete age, whereas the adhesion improved with age for the spray applied systems.

4 Methodology

4.1 Summary of test programme

The performance of the five waterproofing systems when applied to concrete of different ages was assessed by making observations for the presence of pin/blow holes and blisters after waterproofing, and after the slabs were subjected to a thermal shock induced by the application of hot sand, and by measuring the tensile adhesion of the membrane to the concrete at different temperatures.

The waterproofing systems were applied to four different concrete mixtures, namely:

- a gravel aggregate concrete with ordinary cement (CEM1)
- a gravel aggregate concrete with ground granulated blastfurnace slag as a partial cement replacement (CEM1/GGBS)
- a lightweight aggregate concrete including Lytag with CEM1 (Lytag)
- a typical cementitious repair material

These mixtures were chosen because the pore structure of concrete may be different for concrete with ordinary cement (CEM1) compared to concrete with some of the cement replaced by ground granulated blastfurnace slag (GGBS) or pulverized fuel ash (PFA). Therefore, concretes with cement replacements could have a different rate of out-gassing. The bond of the waterproofing system to the concrete may also be different. Note that it was not possible due to practical and operational constraints to include any more specimens in the experimental design, hence mixtures with PFA were not included.

Lightweight aggregate concrete has a lower density and higher porosity than concrete made from normal aggregate. In theory, the increased porosity of lightweight aggregate concrete consists of non-continuous or blind pores in the aggregate, the contents of which would not easily escape from the concrete surface. However, the amount of out-gassing from gravel, limestone or lightweight aggregate concrete may be different.

The methodology can be summarised as follows:

- Slabs were manufactured from four different concrete mixtures and subjected to different curing regimes that varied according to the age at which they were to be waterproofed.
- Slabs, aged 3 days, 7 days, 14 days and 28 days, were waterproofed on the same day. Tack coat was not applied to the waterproofing membrane of any spray applied systems, as would be normal practice prior to surfacing.
- Two days after waterproofing, the membrane was covered with hot sand to replicate the high temperatures encountered during the application of road surfacing material.
- When cooled, the sand was removed and the membrane was examined for pin/blow holes and blisters.
- The tensile adhesion tests were performed on the slabs from 28 days after they were waterproofed to determine the strength of the bond of the waterproofing system to the concrete. The tests were carried out at three temperatures; -10^{o}C, 23^{o}C and 40^{o}C.

The test details for each waterproofing system are summarised in Table 1. A total of 48 slabs were waterproofed and tested with each system. Further details of the methodology, including details of the concrete mixtures and the curing regimes are given below.

Table 1. Test details for each waterproofing system

Concrete mixtures	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Tensile adhesion test temperature -10°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	1	1	1	1	1	1
Repair material	1	1	1	1	1	1
	Tensile adhesion test temperature 23°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	1	1	1	1	1	1
Gravel with CEM1/GGBS	1	1	1	1	1	1
Lytag	1	1	1	1	1	1
Repair material	1	1	1	1	1	1
	Tensile adhesion test temperature 40°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	1	1	1	1	1	1
Repair material	1	1	1	1	1	1

4.2 Preparation of slabs

4.2.1 Specification for concrete mix designs

The slabs were manufactured as specified in BS EN 13375 (2004). Therefore, the concrete mixtures used were based on concrete type MC(0.45) as specified in BS EN 1766 (2000), sub-clauses 6.3.1.2, 6.4 and 6.5. The standard reference concrete mixture requires that ordinary cement type CEM 1 42.4 R compliant with ENV 197-1 (2000) is used with a natural silica-based low water absorption aggregate with a maximum aggregate size of 10mm. The mixture design specifies a water/cement ratio of 0.45 and a cement content of 395 kg/m^3. This mixture design was used for the gravel aggregate concrete with ordinary cement (CEM1).

The CEM1 mixture design was modified to include GGBS in consultation with the manufacturer, Civil and Marine Slag Cement Limited. Fifty percent of the cement was replaced with GGBS and the total cement content was increased to 410 kg/m^3.

The mixture design for the lightweight aggregate concrete was selected in consultation with RMC Lytag. A typical skip mix was chosen with a compressive strength class LC40/44 using 8-4mm Lytag and flint gravel sand. The cement content was 480 kg/m^3.

Maintaining agents were consulted to establish the types of typical cementitious repair materials that are currently used for repairs to bridge decks. As a result of these consultations, a construction repair concrete suitable for reinstatement of large sections of concrete and compliant with BD27/86 (1986) was chosen. The material, a proprietary repair concrete, was pre-bagged and water was added at the time of mixing. It should be noted that polymer modified mortars could behave differently to cementitious materials.

The mixture designs were trialled to check that the consistence was suitable so that the required surface finish could be achieved. Details of the mixtures are given in Table 2.

Table 2. Details of the mixture designs

CEM 1		**CEM1/GGBS**		**Lytag**	
W/C=0.45		W/C=0.45		W/C=0.38	
Cement	395	Cement	205	Cement	480
		GGBS	205		
Laleham sand	650	Laleham sand	650	Laleham sand	656
Laleham 10-5mm	1160	Laleham 10-5mm	1160	Lytag 8-4mm	485
Free water	178	Free water	185	Free water	180

4.2.2 Slab design

The slabs were 300mm square slabs of depth 55mm. BS EN 13375 (2004) specifies that the surface texture of the unformed surface should be between 0.5 and 1.0mm as measured by the sand patch method described in EN 1766 (2000). It should be noted that this differs from the requirements in BD 47/99 (1999) which specifies a U4 finish, i.e. the surface should have a hard dense surface free from screed marks, and should be lightly textured with a wooden float or equivalent so there are no abrupt irregularities more than 3mm.

For the repair material, it was necessary to measure the tensile adhesion within the repair area and at an interface with parent concrete. A composite slab was therefore designed. The concrete substrate was cast using the CEM1 mixture to form a recess in the top surface for the repair material (Figure 1). The concrete substrates were cast with a former in the base of the moulds in advance of the main testing programme and stored for a minimum of 28 days prior to adding the repair material. The top recessed surfaces and the edges of substrates for the repair slabs were lightly grit blasted a minimum of 14 days after casting to provide a key for the repair concrete and the waterproofing.

4.2.3 Slab casting

The method used for casting the slabs followed procedures developed at TRL for producing concrete slabs of consistent quality. A casting schedule was developed to enable the required number of slabs to be waterproofed at each age on the pre-arranged date.

4.2.3.1 Aggregate preparation

Sufficient aggregate and sand was brought into the concrete mixing laboratory at least 24 hours before the start of mixing. A representative sample of each was obtained from each fraction and weighed. The samples were dried in an oven at 105^{o}C overnight, reweighed and the moisture content of each fraction calculated. The batch weights were then calculated to allow for the moisture in the aggregate and sand.

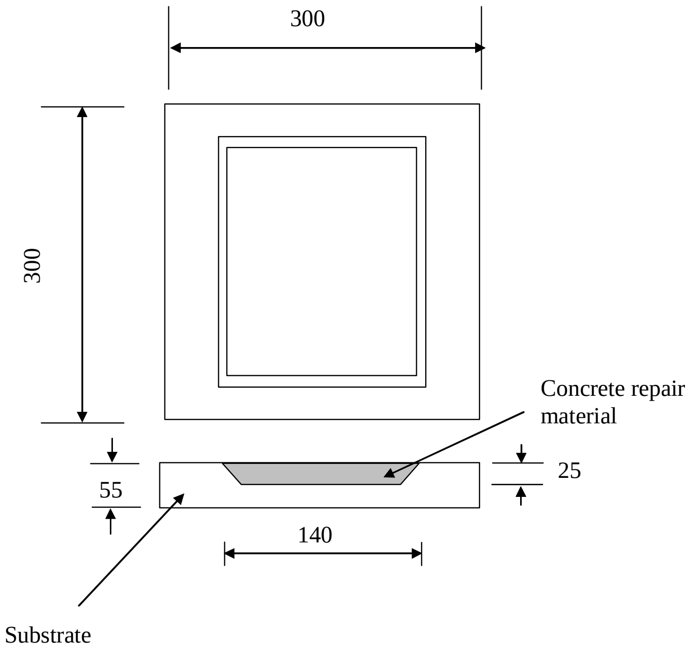

Figure 1. Design of slab for tests on concrete repair material

4.2.3.2 Concrete mixing and casting

The slab moulds were clamped to a vibrating table in the mixing laboratory.

1. Mixing procedure for CEM1, CEM1/GGBS and the substrates for the repair slabs
The component materials were placed in a 50 litre capacity mixer in two stages. The aggregate and water were first mixed for 4 minutes. The cementitious material was added and mixing was continued for a further 3 minutes. The concrete was then placed in the moulds in a single layer and vibrated until fully compacted. The surfaces of the CEM1 and the CEM1/GGBS slabs were finished off with the edge a wooden tamping rod to achieve a "ribbed finish". The substrates for the repair slabs were floated-off smooth with a steel float. The slabs were removed from the table, and cured under damp hessian and polythene for 24 hours.

2. Mixing procedure for Lytag
The specified weight of Lytag was covered with water and soaked for a minimum of 24 hours prior to mixing. Just before mixing, the excess water was drained off and the Lytag and sand were placed in the mixer. The aggregate and water were mixed for 4 minutes before the cement was added and mixed for a further 3 minutes. The concrete was placed in the moulds in a single layer and vibrated until fully compacted. The surface was finished with the edge a wooden tamping rod to achieve a "ribbed finish. The slabs were removed from the table, and cured under damp hessian and polythene for 24 hours.

3. Mixing procedure for repair slabs
The substrates for the repair slabs were placed on a horizontal surface and thoroughly pre-wetted for at least 1 hour prior to mixing. Mixing was accordance with the manufacturer's instructions. A 25 litre capacity mixer was charged with 3.2 litres of water and the entire contents of a 25kg bag of repair concrete was gradually added. Mixing continued for a minimum of 3 minutes. The repair concrete was then placed into the recess of each slab. No vibration was required. It was not possible to produce a ribbed finish on these slabs because of the "jelly like" nature of the repair material in its plastic state. The slabs were cured under damp hessian and polythene for 24 hours.

4.2.3.3 Curing and storage

All the slabs were de-moulded the day after casting. Each slab was weighed and the texture depth on the surface of each slab measured in accordance with the sand patch method described in BS EN 1766 (2000).

The slabs were then stored under damp hessian and polythene until the concrete was an age of 7 days for the 7, 14 and 28-day slabs and 3 days for the 3-day slabs. The 14 and 28-day slabs were then weighed again and moved to the storage area on pallets. Up to 48 slabs could be stored on each pallet in 4 layers. Batons were placed between each layer to protect the textured surface finish and allow air to circulate freely round the slabs.

Although curing under damp hessian is not representative of site conditions, it is considered that it had the same affect as curing compounds and avoided the need to remove the compounds prior to waterproofing.

The vertical edges of the CEM1, CEM1/GGBS and Lytag slabs for Systems 1 to 4 were scabbled to provide a key for the waterproofing system. The surfaces and vertical edges of the System 5 slabs were grit blasted.

Some slabs were waterproofed after they had been immersed in water for about 60 hours prior to waterproofing. On the morning of the waterproofing, the slabs were removed from the water, surface dried, weighed and left to dry until they were prepared for the application of the primer.

The curing regimes are summarised in Table 3.

Table 3. Curing regimes

Age and condition of concrete when waterproofed	Curing regime
3 days	Stored under wet hessian then allowed to surface dry for two hours before waterproofing
7 days	Stored under wet hessian then allowed to surface dry for two hours before waterproofing
14 days (DRY)	Stored under hessian for 6 days then allowed to dry
14 days (WET)	Stored under hessian for 6 days, allowed to dry for 4.5 days, immersed in water for 2.5 days until 3 hours before waterproofing
28 days (DRY)	Stored under hessian for 6 days then allowed to dry
28 days (WET)	Stored under hessian for 6 days, allowed to dry for 11.5 days, immersed in water for 2.5 days until 3 hours before waterproofing

4.3 Moisture content

An electronic surface moisture meter was purchased in order to measure the surface moisture content of the slabs at different stages during their curing and storage. After discussions with the manufacturer, TRL was advised that a probe which made contact with the concrete through foam pads would be suitable. However, it was found in use that over 5 successive mixing days the measured moisture content of slabs cast with the same mix design (CEM1) the day after casting reduced from 6.5% to 4.1% (Table 4). Clearly this was not possible, so a fault in the measurement was suspected. The meter and the probe were returned to the manufacturer who found them to be functioning correctly, but the reduction in the measured moisture content was occurring because the foam pads had become clogged with concrete dust. The manufacturer was unable to offer any solution to the problem other than suggesting that new pads were fitted to the probe. Since TRL considered it very likely that the problem would recur, TRL asked if it would be possible to check the calibration on every occasion before and after use, but the manufacturer was unable to suggest a suitable calibration method. It was felt that this method of measurement was unsatisfactory and it was therefore abandoned. Instead, a gravimetric method was devised to determine the bulk moisture content of the slabs.

Table 4: Measured moisture content of slabs the day after casting

Date of casting	The mean measured moisture content the day after casting (%)
24 October 2005	6.5
7 November 2005	5.8
14 November 2005	5.0
18 November 2005	4.4
28 November 2005	4.1

The gravimetric method relies on determining the moisture content of 100mm cubes cast from each batch of concrete which are cured with the slabs under hessian up to an age of 7 days. The cubes, then assumed to be in a saturated surface dry (SSD) condition, are weighed, dried in an oven for 7 days at 105^{o}C and reweighed. The difference in the weights is used to calculate the moisture content of the concrete in a SSD condition. From this, and the weight of each slab after curing under hessian, the oven dry weight of each slab is estimated and this value is used to estimate the moisture content of the slabs at various stages prior to waterproofing. This method was applicable to the slabs cast from the CEM1, CEM1/GGBS and Lytag mixtures only. The repair slabs were a composite of the CEM1 mixture substrate and the repair concrete. As the substrate had been kept in a dry environment prior to casting the repair insert, the slabs would not have been in a SSD condition at the end of the curing period and hence it was not possible to estimate their oven dry weight and bulk moisture content.

It was not thought necessary to use the gravimetric method to measure moisture content before the moisture meter was found to be faulty during the testing of the first two systems. Therefore, no cube data are available for this system. However, the bulk SSD moisture contents were estimated from cubes cast for other waterproofing systems, and these values are given in Table 5.

Table 5. Estimated bulk SSD moisture content of slabs used for Systems 1 and 2

Mixture design	**Age at end of curing under hessian**	
	3 Days	**7 Days**
	Bulk moisture content (%)	
CEM1	6.6	7.0
CEM1/GGBS	7.6	8.4
Lytag	16.4	18.2

For Systems 3 to 5, three cubes for the determination of saturated surface dry moisture content were cast with each batch of concrete. The results are given in Table 6.

Table 6. Estimated bulk SSD moisture content of slabs used for Systems 3 to 5

Mixture design	Age at time of waterproofing (days)			
	3	7	14	28
	Bulk moisture content (%)			
System 3				
CEM1	6.2	6.1	7.0	7.4
CEM1/GGBS	7.2	7.2	7.2	9.0
Lytag	16.7	20.5	16.3	18.7
System 4				
CEM1	6.1	7.0	6.3	6.7
CEM1/GGBS	6.2	7.2	7.7	7.3
Lytag	17.3	16.3	17.2	18.4
System 5				
CEM1	6.7	5.9	6.6	7.1
CEM1/GGBS	7.8	6.8	7.1	7.9
Lytag	15.0	14.5	17.5	18.4

4.4 Application of the waterproofing system

Systems 1 to 3 were spray applied systems, System 4 was a 'pour-and-roll' sheet system and System 5 was a 'torch-on' sheet system.

The overall objective was that the applicators would prepare the slabs and apply their waterproofing system using similar procedures that they would use on bridge decks. Each waterproofing system was applied to all 48 slabs for that system at the same time. The 16 slabs that had been immersed in water for 60 hours were removed from the tank, surface dried with a cloth and then weighed in a saturated surface dry condition. These slabs were allowed to dry for between 2 and 5 hours prior to surface preparation. Details of the waterproofing systems and the method of surface preparation undertaken by the manufacturers is given in Table 7. The slabs were weighed at each stage of the surface preparation to allow the changes in the bulk moisture content to be monitored. Figure 2 shows a typical method of drying the slabs with a blow torch.

Before the application of the spray applied systems, the manufacturers checked the air temperature, relative humidity and the surface temperature of the slabs to calculate the dew point to ensure that the climatic conditions were within the specified limits for application of bridge deck waterproofing systems. Waterproofing was carried out at temperatures within the range 6 to 11ºC.

Table 7: Details of the waterproofing systems and surface preparation

System	Waterproofing type	Surface preparation
1	Spray applied	All the slabs were wire brushed and loose material was removed with compressed air. The repair slabs were wiped with a cloth saturated with acetone. Some of the 3 and 7 days slabs were lightly dried with a gas flame.
2	Spray applied	All the slabs were wire brushed and loose material was removed with a soft brush. The surface was then dried with a flame torch and the surface moisture content was measured with the manufacturer's electronic meter. Slabs with a surface moisture content greater than 6% were dried further until the surface moisture content was 6% or less.
-3	Spray applied	All the slabs were wire brushed and loose material was removed with a soft brush. A total of ten of the wetter looking 3-day, 7-day and wet slabs were then surface dried with a gas flame.
4	Pour-and-roll	The 14-day and 28-day dry slabs were wire brushed prior to waterproofing. The slabs that had been immersed for 60 hours were first dried with a gas flame, then wire brushed and finally dried with a gas flame for a second time. All the 3-day and 7-day slabs were dried with a gas flame and then wire brushed.
5	Torch-on	All the slabs were grit blasted on the day they were primed and then dried with a gas flame.

After surface preparation, all the slabs for the three spray systems and the pour-and-roll system were laid out on pallets. Each slab was supported on battens outside in the works yard at TRL. The primer was then brush applied to the textured top surface and the edges of each of the slabs. The waterproofing membrane of the spray applied systems was applied about one hour after priming. The membrane of Systems 1 and 3 was applied in two coats and that of System 2 was applied as one coat. A typical application a spray applied membrane is shown in Figure 3. The primer of System 4 had to be left to dry for a few hours before the membrane could be applied. Because of time constraints, it was necessary to apply the membrane to some of the slabs on the following day. The sheet membrane was cut to size and applied to the textured surface and the sides of each slab. Bitumen was heated until molten and then poured onto the surface and sides of the slabs. The sheet membrane was unrolled into position on the top of the slabs, folded down the sides (Figure 4), and pressed down firmly down to form a good bond. As requested by TRL, the normal procedure for apply the membrane to corners such as those on the slabs was not adopted. Therefore, the membrane was not fully waterproof at the corners, but this was not necessary for these tests.

Priming of the slabs waterproofed with System 5 was carried out in a laboratory. Approximately 30 to 40g of primer was poured onto the surface of the slabs and spread evenly using a small roller. The edges of each slab were primed by brushing. Fire dried quartz sand (0.2 – 0.7mm) was sprinkled onto the top surface of the slabs at a target rate of 1kg/m^2 before the primer started to cure. The primed slabs were left to cure at a temperature of 23ºC for about 24 hours prior to the application of the waterproofing. The sheet membrane was applied to sets of five slabs which were placed in a line in the works yard (Figure 5). Strips of membrane, slightly wider than the width of the slabs, were rolled up and placed at one end of the line of slabs (a). The bitumen backing of the sheet was heated with a gas flame until it was fluid as the sheet was unrolled (b) until it covered all five slabs. The membrane was pressed down onto the concrete so it bonded to the primer as the bitumen cooled (c). Finally, the sheets were trimmed with a sharp knife (d). System 5 includes a 35mm layer of 0/8mm Güssasphalt which is applied at temperatures up to 240ºC. The Güssasphalt fuses with the bitumen in the membrane to achieve the required waterproofing integrity. The membrane was not overlaid with Güssasphalt for these tests because the main concern was the bond of the waterproofing system to the concrete substrate.

No pinholes or blisters were evident on any of the slabs at any time after the membranes had been applied.

Figure 2. Drying the slabs prior to the application of the primer

Figure 3. Application of the second coat of a spray applied waterproofing membrane

Figure 4. Application of sheet waterproofing membrane

(a) Primed slabs

(b) Torching-on the membrane

(c) Membrane immediately after application

(d) Trimming membrane with a knife

Figure 5. Application of sheet membrane

4.5 Hot sand conditioning test

In order to check that the waterproofing system would withstand the effect of the application of hot road surfacing materials when applied to concrete less than 28 days old, the membrane was overlaid with hot sand two days after waterproofing. It was necessary to ensure that any vapour produced by out-gassing during the test would be constrained within the slabs. This was achieved by sealing the sides as well as the top surfaces of the slabs with the primer and waterproofing membrane (primer only for System 5), and by placing the slabs on a sheet of 6mm rubber which was sufficiently pliable to take up irregularities in their bottom faces.

The slabs were placed within a wooden frame laid over the sheet of rubber, and separated by wooden partitions within the frame into groups of four. Thermocouples were placed on the surfaces of the slabs, and the surfaces of the slabs were fully covered with thin gauge aluminium foil (Figure 6). The temperature was logged every 10 seconds when the hot sand was poured.

Trays containing 26kg of sand were heated to 220 or 230ºC. The hot sand was then quickly poured over each group of 4 slabs so they were evenly covered to a depth of 75mm (Figure 7). Immediately after pouring, the sand was covered with a lid and the slabs were left for at least two hours. This procedure was broadly in accordance with the method specified in Clause B4.2(j) of BD 47/99, which simulates the thermal shock experienced by waterproofing systems when they are overlaid with hot surfacing materials which indicates material should be heated to approximately 240ºC to achieve a temperature of 145±5ºC at the surface of the membrane.

Prior the start of the main programme, trials were carried out to determine the most appropriate temperature to achieve the target temperature of 145ºC. It was found that there were large variations in the maximum temperature measured on the individual slabs. Possible reasons for this are that, although the sand was transferred from the oven to the slabs without delay, the sand exposed to ambient temperature would have cooled quicker than the sand from within the bulk. In addition, the sand had to be spread out so it covered the edges of each block of four slabs, and this would have introduced further variations in the temperature distribution. The maximum temperature recorded by each thermocouple would have been dependent on the temperature of the sand that covered it, hence where the sand came from.

The sand was heated for 220ºC for System 1 and 230^{o}C for Systems 2 to 5. Figure 8 shows a typical record of the variation in surface temperature of the slabs for two thermocouples within a set four slabs when the hot sand was applied. It can be seen that the temperature rose almost instantaneously up to maximum values of 137 ^{o}C and 157^{o}C for the two thermocouples. Table 8 gives the mean and range of maximum measured surface temperatures measured for each sections. Several measurements were outside the limits of 145±5^{o}C given in BD47/99, but this is not considered to be significant because the main aim was to ensure that the surface temperatures were high enough to produce a vapour pressure within the concrete that could cause blistering of susceptible membranes.

After two hours, the sand and aluminium foil were removed and the membranes were examined for signs of blistering but none were found on any of the systems.

Clause 901.9 of the SHW (MCHW 1) states that:

> '*With the exception of sand asphalt carpet, bituminous materials with a temperature greater than 125°C shall not be deposited on a bridge deck waterproofing system unless adequate precautions are taken to avoid heat damage in accordance with a good industry practice. A maximum temperature of 145°C is permitted for sand asphalt carpet.*'

The above shows that surfacing laid at temperatures up to 145 ^{o}C would raise the temperature of the substrate and waterproofing system to temperatures significantly lower than those encountered in the hot sand conditioning tests. Therefore the risk of out-gassing during surfacing would be correspondingly lower on bridges than in these tests. On bridges, the surfacing must be laid and compacted at a temperature that is sufficiently high to active any tack coat that is present and form a good bond between the surfacing and the waterproofing system. The temperature that the waterproofing system must reach during compaction to achieve this ranges from about 80^{o}C to 100^{o}C, dependent on the system. The measurements made during the hot sand tests suggest that these temperatures may not be achieved if surfacing is laid at temperatures much lower than those specified in Clause 901.9 and/or is not compacted soon after laying.

Figure 6. Slabs placed within a frame in groups of four and covered with aluminium foil

Figure 7. Hot sand conditioning test in progress

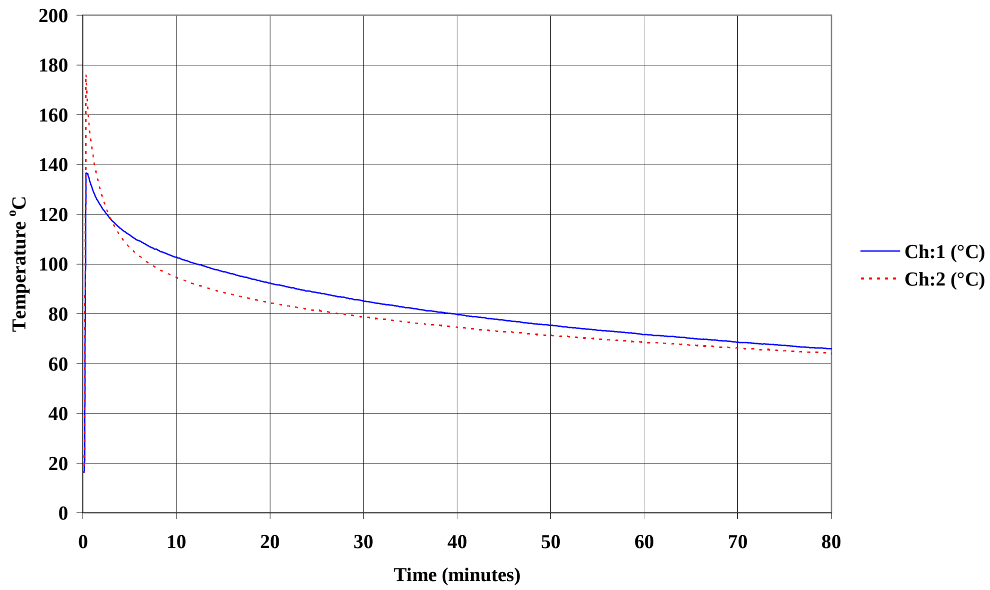

Figure 8. Variation of measured surface temperature of slabs with time for hot sand test

Table 8. Mean and range of maximum temperatures measured for each system

System	Range of maximum measured surface temperature (°C)		
	Mean	Min	Max
1	142	121	181
2	147	139	167
3	152	127	183
4	161	137	185
5	155	125	180

4.6 Tensile adhesion tests

Tensile adhesion tests were carried out on the waterproofed slabs a minimum of 28 days after they were waterproofed to determine the strength of the bond of the waterproofing system to the concrete. The tests were carried out in accordance with BS EN 13596 (British Standards Institution, 2004) at the three temperatures specified in Clause B4.2(d) of BD47, i.e. -10±2ºC, 23±2ºC, and 40±2ºC.

Three tests were carried out on the waterproofed face of each slab cast from the CEM1, CEM1/GGBS and Lytag mixtures (Figure 9). For the repair materials, two tests were carried out within the repaired area and two tests were carried out over the interface between the repaired area and the substrate (Figure 10).

The test areas were isolated by cutting circular slots around the circumference of the test sections through the waterproofing and about 3mm into the concrete. The 50mm diameter test dollies were glued to the surface of the waterproofing membrane using an adhesive recommended by the supplier of the waterproofing system. The bond strength was then determined using a Limpet pull-off tester which applied a tensile force normal to the plane of the waterproofing system.

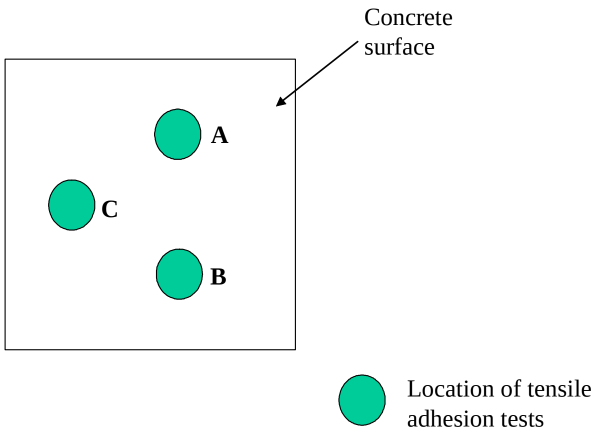

Figure 9. Locations of the tensile adhesion tests on CEM1, CEM1/GGBS slabs

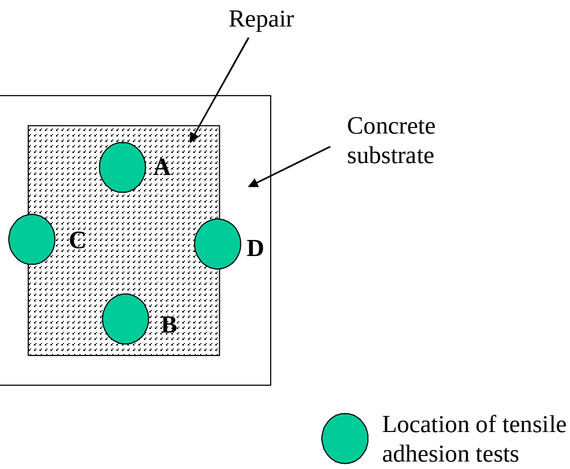

Figure 10. Locations of tensile adhesion tests on repair slabs

5 Results

5.1 Texture depth measurements

The mean, minimum and maximum texture depths for the slabs with each mixture design are given in Table 9. The mean values for each system for each mixture design were within the limits specified in BS EN 133755 (2004) . The mean texture depth for the CEM1 slabs (0.57mm) was similar to the value for the CEM1/GGBS slabs (0.61mm), whereas the texture depth of the Lytag slabs was higher at 0.80mm. However, 26% and 13% of the measurements on the CEM1 and CEM1/GGBS were less than 0.5mm and 20% of the measurements on the Lytag slabs were greater than 1.0mm. The minimum texture depth measured on the CEM1 and CEM1/GGBS slabs were 0.40mm and 0.41mm respectively and the maximum for the Lytag slabs was 1.46mm. None of the measurements on the CEM1 and CEM1/GGBS slabs was greater than 1.0mm. Four of the measurements on the Lytag slabs less than 0.5mm.

Despite the fact that some of the measurements were outside the limits specified in BS EN 13375, the deviations were relatively small and the measurements were consistent between all five systems. It is unlikely that the difference measured in texture depth would have affected the results significantly.

Table 9. Texture depth measurements

System	Texture depth (mm)		
	Mean	Minimum	Maximum
CEM 1			
S1	0.58	0.44	0.87
S2	0.60	0.46	0.84
S3	0.56	0.44	0.73
S4	0.54	0.40	0.69
S5	0.58	0.45	0.68
CEM1/GGBS			
S1	0.74	0.41	0.95
S2	0.67	0.53	0.81
S3	0.54	0.48	0.64
S4	0.58	0.48	0.66
S5	0.56	0.46	0.65
Lytag			
S1	0.90	0.82	1.05
S2	0.84	0.63	1.15
S3	0.81	0.47	1.46
S4	0.68	0.43	0.95
S5	0.74	0.44	0.95

5.2 Moisture content of slabs

Figure 11 shows the mean bulk moisture content of the dry CEM1 slabs waterproofed at different ages immediately before waterproofing. It is evident that the moisture content of 3 and 7 day slabs were close to saturation, whereas the moisture content of 14 and 28 day slabs were much lower. For example, the moisture content of the 28-day and 3-day System 2 slabs were 4.8% and 6.4% respectively. The bulk moisture content immediately prior to waterproofing of the 28 and 14 day wet and dry slabs from each mixture design is given in Table 10. The moisture content of the dry slabs were, on average, 20% less than the moisture content of the wet slabs. The results were similar for the CEM1/GGBS and Lytag slabs. The variation in the bulk moisture content immediately prior to the application of the waterproofing for the different systems arose from the inherent variation which is normal for concrete production, small differences in the environmental conditions during the curing, and the different drying regimes adopted by the manufacturers.

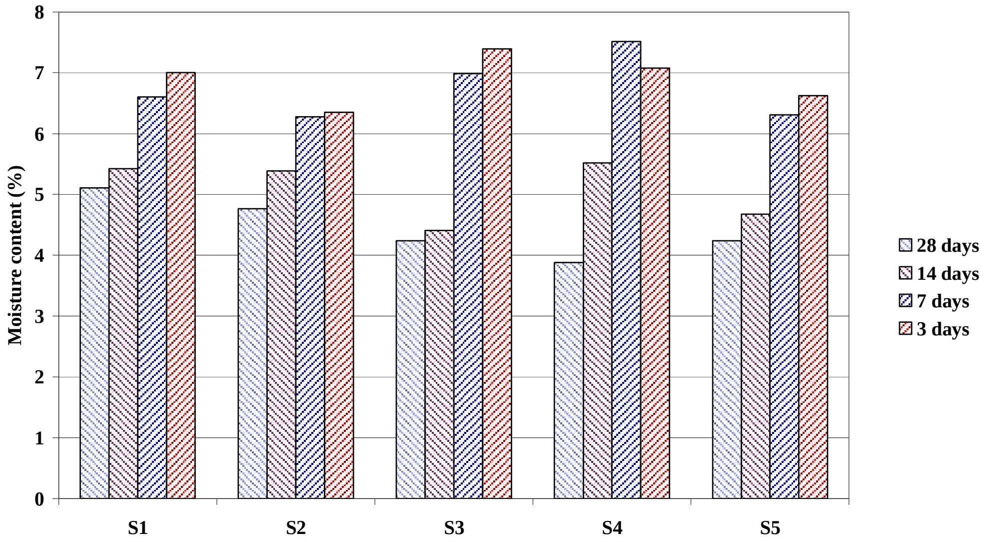

Figure 11. Mean bulk moisture content of dry CEM1 slabs immediately prior to waterproofing

Table 10. Bulk moisture content of dry and wet slabs immediately prior to waterproofing

Condition	System				
	1	**2**	**3**	**4**	**5**
CEM1 - 28 days					
Dry	5.1	4.8	4.2	3.9	4.2
Wet	6.1	6.1	5.6	5.3	5.9
CEM1 - 14 days					
Dry	5.4	5.4	4.4	5.5	4.7
Wet	6.6	6.2	5.9	6.6	5.9
CEM1/GGBS - 28 days					
Dry	6.2	5.2	4.9	4.2	5.0
Wet	7.0	6.6	6.6	5.4	7.1
CEM1/GGBS - 14 days					
Dry	6.3	6.6	5.5	5.6	5.8
Wet	7.7	7.5	6.9	6.7	6.7
Lytag - 28 days					
Dry	11.1	-	8.8	8.8	8.1
Wet	13.0	11.6	12.5	11.7	9.5
Lytag - 28 days					
Dry	11.7	8.8	13.0	10.8	9.6
Wet	12.3	17.0	17.2	13.6	13.4

All the manufacturers used a gas flame to dry the slabs to varying degrees. In order to assess the effect of this on the moisture content of concrete, the data obtained for one of the systems has been analysed in detail. The 16 slabs 14-day and 28-day slabs that had been immersed for approximately 60 hours were weighed immediately after they had been surface dried. The slabs were then allowed to air dry for about 3 hours before the top surface of each slab was dried for less than 1 minute using a gas flame. The manufacturer then measured the surface moisture content of each slab with an electronic moisture meter. All the slabs were reweighed at this stage. The slabs with a surface moisture content greater than 6% were dried for a second period. The surface moisture content was again measured and the slabs were reweighed. The weights of the slabs at each stage were used to calculate their bulk moisture content. The results are given in Table 11.

The bulk moisture content of the CEM1 and CEM1/GGBS slabs that had been immersed in water for 60 hours reduced by a maximum of 0.3% during the periods of air and flame drying. By contrast, the bulk moisture content of the Lytag slabs reduced by about 1%.

The surface moisture measurements of the CEM1, CEM1/GGBS and Lytag slabs ranged from 4.5% to 11% after the first period of flame drying. It was necessary to flame dry only four 14-day slabs and one 28-day slab a second time, whereas all the slabs waterproofed at ages of 7 and 3 days required a second period of flame drying. The surface moisture content reduced dramatically during the second flame drying period, in some cases reducing to zero. By contrast, the bulk moisture content typically reduced by values less than 0.5%, despite fairly strong flame drying. Clearly, the changes in the surface moisture content are localised readings and have a small effect on the overall bulk moisture content of the concrete.

Table 11. Bulk and surface moisture content of slabs after immersion and after first and second periods of flame drying

Adhesion test temperature	**Time of measurement**	**3 days**		**7 days**		**14 days**				**28 days**			
						Dry		**Wet**		**Dry**		**Wet**	
		Moisture Content (%)											
		A[1]	**B[2]**	**A[1]**	**B[2]**	**A[1]**	**B[2]**	**A[1]**	**B[2]**	**A[1]**	**B[2]**	**A[1]**	**B[2]**
CEM1													
-10°C	After immersion							6.6				6.3	
	After first drying	6.8	11	6.5	8	5.5	6.5	6.4	7	4.8	5.5	6.1	6
	After second drying	6.4	2	6.3	4	5.4	0	6.0	0	-	-	-	-
23°C	After immersion							5.6				6.3	
	After first drying	6.4	10	6.7	8	5.3	6	5.3	5.5	4.9	6	6.1	5.5
	After second drying	6.1	0	6.3	0	-	-	-	-	-	-	-	-
40°C	After immersion							7.6				6.4	
	After first drying	6.8	7	6.5	7.5	5.4	6	7.6	8	4.6	5.5	6.1	5.5
	After second drying	6.3	0	6.3	0	-	-	7.3	0	-	-	-	-
CEM1/GGBS													
23°C								7.6				7.0	
	After first drying	8.1	10	7.6	10	6.6	5.5	7.6	7	5.2	6	6.6	8
	After second drying	7.8	4	7.3	2	-	-	7.5	3	-	-	6.5	5.5
Lytag													
23°C	After immersion							18.3				12.8	
	After first drying	16.5	9	14.6	9	8.8	4.5	17.3	4.5	-	6.5	11.6	5.5
	After second drying	15.7	5	13.8	3	-	-	-	-	-	3	-	-
REPAIR[3]													
-10°C	After first drying	-	7	-	7.5	-	5	-	7		5	-	6.5
	After second drying	-	0	-	0	-	-	-	0		-	-	0
23°C	After first drying	-	8	-	8	-	5	-	8		5.5	-	6.5
	After second drying	-	0	-	0	-	-	-	0		-	-	0
40°C	After first drying	-	7.5	-	10	-	6	-	7.5		5	-	6
	After second drying	-	0	-	0	-	-	-	0		-	-	-

1: A: Bulk moisture content measured gravimetrically

2: B: Surface Moisture content measured with the manufacturer's electronic moisture meter

3: It was not possible to measure the bulk moisture content of the composite repair specimen (see Section 4.3)

5.3 Tensile adhesion tests

The mean of the failure stresses measured in the tensile adhesion tests on each slab, expressed as a percentage of the failure stresses measured on the dry 28-day slabs at the appropriate temperature, are shown in Table 12, Table 15, Table 18, Table 21 and Table 24. In order to compare the mean failure stresses measured on the different types of slab, they are expressed as a percentage of the failure stresses measured on the dry CEM1 28-day slabs at the appropriate temperature in Table 13, Table 16, Table 19, Table 22 and Table 25.

The failure surfaces on the slabs and the dollies were examined to determine where the bond had failed. The locations where most of the failure occurred on each slab are shown in Table 14, Table 17, Table 20, Table 23 and Table 26. The locations of the failure surfaces at the interface between the repair material and the concrete substrate of the repair slabs have been identified separately for the repair material (R) and the substrate (S).

For all five systems, none of the slabs showed any signs of pin/blow holing or blistering at any time during the test programme.

The requirements for adhesion strength specified in Clause B4.2(d) of BD 47 are 0.3MPa at -10°C and 23°C, and 0.2MPa at 40°C,

5.3.1 System 1

All of the failure stresses exceeded the minimum requirements specified in Clause B4.2 (d) of BD 47 even though some of the 3-day and 7-day slabs were not flame dried. At a test temperature of 23°C, the mean failure stresses were higher for the 3-day and 7-day slabs than for the 28-day slabs (Table 12). At -10°C and 40°C, the mean failure stresses for the 3-day and 7-day slabs ranged from 82 to 150% of those for the corresponding 28-day slabs.

The mean failure stresses for the wet and dry 14-day slabs ranged from 91 to 191% and 101 to 144% respectively of those for the 28-day dry slabs, with all but one of the percentages for the wet slabs being below 100%. The mean failure stresses for the 28-day wet slabs ranged from 68 to 119% of those for the dry 28-day slabs. Therefore, the lowest stresses, expressed as a percentage, were measured on the 28-day wet slabs.

The mean failure stresses were generally higher for the CEM1 slabs than for the CEM1/GGBS and Lytag slabs at 23°C (Table 13). They were higher and generally higher for the repair slabs than for the CEM1 slabs at -10°C and 23°C, respectively, but generally lower for the repair slabs than for the CEM1 slabs at 40°C.

At -10°C, the failure surfaces were mainly within the concrete or at the surface of the concrete (Table 14). At 23°C, the failure surfaces were mainly at the surface of the concrete, but the repair slabs tended to fail between the primer and the repair material. At 40°C, the failure surfaces were mainly between the primer and the concrete or the primer and the membrane.

Table 12. System 1: Tensile adhesion test failure stresses as a percentage of dry 28-day results

Concrete mixtures	Mean failure stress as percentage of dry 28-day result (%)					
	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Tensile adhesion test temperature -10°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	100	89	114	120	100	115
Repair surface	112	82	105	110	100	89
Repair/Substrate interface	99	145	101	112	100	118
	Tensile adhesion test temperature 23°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	130	124	140	143	100	115
Gravel with CEM1/GGBS	163	144	144	150	100	105
Lytag	160	189	126	111	100	91
Repair surface	153	164	133	191	100	119
Repair/Substrate Interface	109	113	103	91	100	68
	Tensile adhesion test temperature 40°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	117	127	125	142	100	100
Repair surface	93	150	122	119	100	86
Repair/Substrate interface	124	118	128	104	100	97

Table 13. System 1: Tensile adhesion test failure stresses as a percentage of dry CEM1 28-day results

Concrete mixtures	Mean failure stress as percentage of dry 28-day result (%)					
	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Tensile adhesion test temperature -10°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	100	89	114	120	100	115
Repair surface	161	118	151	158	143	127
Repair/Substrate interface	119	173	120	134	120	141
	Tensile adhesion test temperature 23°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	130	124	140	143	100	115
Gravel with CEM1/GGBS	126	111	111	116	77	82
Lytag	123	145	97	85	77	69
Repair surface	153	164	133	191	100	119
Repair/Substrate Interface	140	144	131	116	128	87
	Tensile adhesion test temperature 40°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	117	127	125	142	100	100
Repair surface	88	142	116	114	95	82
Repair/Substrate interface	120	114	123	101	97	94

Table 14. System 1: Location of failure surfaces during tensile adhesion tests

Concrete mixtures	**Location of failure surface**					
	Concrete age at time of application of waterproofing (days)					
	3	**7**	**14**		**28**	
	Pull-off test temperature -10°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	CS	C	CS	C	CS	PC
Repair surface	CS	C/CS	CS	C/CS	CS	CS
Repair/Substrate interface	CS(S) CS(R)	CS/PC(S) PC(R)	CS/PC(S) CS(R)	CS(S) CS(R)	CS(S) C/PC(R)	CS(S) PC(R)
	Pull-off test temperature 23°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	CS	CS	CS	CS	PC	CS
Gravel with CEM1/GGBS	C	CS	CS	C	CS	CS
Lytag	CS	CS	PM	PM	CS	CS
Repair surface	CS	PC	CS/PC	PC	PC	PC
Repair/Substrate Interface	CS(S) CS(R)	PC(S) PC(R)	CS(S) PC(R)	CS(S) PC(R)	CS(S) PC(R)	PC(S) PC(R)
	Pull-off test temperature 40°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	PM	PM/CS	PC	PM	PM	PC
Repair surface	PC	PC	PC	PM	PC	PC
Repair/Substrate interface	PC(S) PC(R)	PC(S) PC(R)	PC(S) PC(R)	PM/PC(S) PM.CS(R)	CS(S) PC(R)	CS(S) PC(R)

Key

C = failure within concrete

CS = failure at surface of concrete

PC = failure between primer and concrete

PM = failure between primer and membrane

(S) = on substrate

(R) = on repair material

5.3.2 System 2

When the manufacturer of System 2 carries out tensile adhesion tests, the dollies are normally placed on the membrane as it cures so they bond well to the membrane. The hot sand conditioning prevented this method for these tests so it was necessary to use an adhesive. The adhesive was chosen after obtaining advice from manufacturer and was considered to be the best for the purpose. However, the manufacturer indicated that, as found in these tests, the bond of the adhesive to the membrane was likely to fail at high stresses.

When the adhesive failed in a tensile adhesion tests, the tensile bond of the waterproofing system to the substrate would have been higher than the failure stress measured. Therefore, some of the percentages in Table 15 and Table 16 are prefixed with > or < to indicate that the percentage would have been, respectively, higher or lower than the value shown. Where a percentage is shown in parenthesis, the adhesive failed in at least one of the tests on both slabs used for the calculation.

All of the failure stresses measured in the tensile adhesion tests exceeded the minimum requirements specified in Clause B4.2(d) of BD 47. The mean failure stresses generally exceeded the requirements by a considerable margin, but some individual results were only slightly above the minimum requirements. The three lowest failure stresses of all those measured were on three repair slabs: two within the repair material (3-day slab tested at 23^{o}C and 28-day wet slab tested at 40^{o}C) and one at the repair/substrate interface (28-day wet slab tested at 40^{o}C). A significant proportion of all three failure surfaces was at the primer.

It is difficult to compare the results for the different substrates because the bond of the adhesive to the membrane failed in many tests, However, except for the 3-day old repair slab, at 23°C the failure stresses were higher (in some cases significantly higher) for the repair material than for the repair/substrate interface of the repair slabs and the CEM1, CEM1/GGBS and Lytag slabs.

At -10°C, the failure stresses were higher for the repair material of the repair slabs than for the CEM1 slabs. Also, the failure stresses were generally higher for the repair/substrate interface of the repair slabs than for the CEM1 slabs.

At 40°C, except for the 28-day old wet repair slab, the failure stresses were higher for the repair material than for the repair/substrate interface of the repair slabs and the CEM1 slabs. Also, the failure stresses were generally higher for the CEM1 slabs than for the repair/substrate interface of the repair slabs.

There were no adhesive failures in the tests on the CEM1 slabs at -10°C. The mean failure stresses for the 3-day old, 7-day old and 14-day old wet slabs were 65, 129 and 71%, respectively, of those for the 28-day old dry slab. The mean failure stresses for the 14-day old dry slab, and the 28-day old wet and dry slabs were similar.

In the tests at 40°C on the repair/substrate interface of the repair slabs, the adhesive failed only in the tests on 14-day old wet slab, but the mean failure stress was only 5% less than that of the 28-day old dry slab. The mean failure stresses for the 3-day old, 7-day old, 14-day old dry and 28-day old wet slabs were 49, 57, 80 and 79%, respectively, of those for the 28-day old dry slab.

Most of the specimens were flame dried fairly strongly before their moisture content was considered to be low enough for the application of the waterproofing system. A surface moisture content of 0% was recorded for 18 of the 48 slabs; the previous value being in excess of 6% (Table 11).

Two of the three lowest failure stresses were measured on slabs with a surface moisture content of 0%. Therefore, it is possible that the low failure stresses were because insufficient time was left for the primer to cure, rather than because the curing of the primer was affected by the presence of moisture. Certainly, apart for the second lowest failure stress, the higher surface moisture content of the other slabs did not appear to have a detrimental effect on their failure stresses, including the Lytag slabs which had the highest bulk moisture content. However, the mean failure stresses of the 3-day slabs were generally lower than those of the 28-day dry slabs and tended to be lower than those of 7-day slabs.

Table 15. System 2: Tensile adhesion test failure stresses as a percentage of dry 28-day results

Concrete mixtures	Mean failure stress as percentage of dry 28-day result (%)					
	Concrete age at time of application of waterproofing (days)					
	3	**7**	**14**		**28**	
	Tensile adhesion test temperature -10°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	65	129	104	71	100	101
Repair surface	(41)	(78)	(89)	(52)	100	(53)
Repair/Substrate interface	<64	(59)	(104)	(86)	100	(114)
	Tensile adhesion test temperature 23°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	<64	<89	(120)	<140	100	(98)
Gravel with CEM1/GGBS	<68	<81	(114)	(97)	100	(98)
Lytag	(89)	(80)	(83)	(59)	100	(93)
Repair surface	<20	(93)	(114)	(92)	100	(96)
Repair/Substrate Interface	68	>41	>65	>60	100	61
	Tensile adhesion test temperature 40°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	66	109	>151	>156	100	>120
Repair surface	<81	(112)	(111)	(101)	100	(31)
Repair/Substrate interface	49	57	80	>95	100	79

Note:

The prefix > indicates that the bond of the adhesive to the membrane failed in at least one of the tensile adhesion tests on the slab in question, but not in any of the tests on the 28-day old slab. In these cases, the true percentages would have been higher than the values shown.

The prefix < indicates that the bond of adhesive to the membrane failed in at least one of the tensile adhesion tests on the 28-day old slab, but not in any of the tests on the slab in question. In these cases, the true percentages would have been lower than the values shown.

Where the percentage is given in parenthesis, the bond of adhesive to the membrane failed in at least one of the tensile adhesion tests on the slab in question, and in at least one of the tests on the 28-day old slab. In these cases, the true percentages could have been higher or lower than the percentages shown.

Table 16. System 2: Tensile adhesion test failure stresses as a percentage of dry CEM1 28-day results

Concrete mixtures	Mean failure stress as percentage of dry 28-day result (%)					
	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Tensile adhesion test temperature -10°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	65	129	104	71	100	101
Repair surface	>95	>180	>207	>120	>233	>122
Repair/Substrate interface	73	>67	>119	>98	>114	>130
	Tensile adhesion test temperature 23°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	<64	<89	(120)	<140	100	(98)
Gravel with CEM1/GGBS	<66	<79	(111)	(95)	(98)	<96
Lytag	(136)	(122)	(127)	(90)	(153)	(143)
Repair surface	<39	(179)	(220)	(177)	(193)	(185)
Repair/Substrate Interface	<98	(60)	(94)	(86)	<145	<89
	Tensile adhesion test temperature 40°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	66	109	>151	>156	100	>120
Repair surface	153	>211	>209	>191	>189	>58
Repair/Substrate interface	61	72	101	>119	126	99

Note:

The prefix > indicates that the bond of the adhesive to the membrane failed in at least one of the tensile adhesion tests on the slab in question, but not in any of the tests on the 28-day old CEM1 slab. In these cases, the true percentages would have been higher than the values shown.

The prefix < indicates that the bond of adhesive to the membrane failed in at least one of the tensile adhesion tests on the 28-day old CEM1 slab, but not in any of the tests on the slab in question. In these cases, the true percentages would have been lower than the values shown.

Where the percentage is given in parenthesis, the bond of adhesive to the membrane failed in at least one of the tensile adhesion tests on the slab in question, and in at least one of the tests on the 28-day old CEM1 slab. In these cases, the true percentages could have been higher or lower than the percentages shown.

Table 17. System 2: Location of failure surfaces during tensile adhesion tests

Concrete mixtures	Location of failure surface					
	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Tensile adhesion test temperature -10°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	CS	CS/PM	CS	C	CS	CS
Repair surface	A	A	A	A	A	A
Repair/Substrate interface	CS(S) PM(R)	A(S) A(R)	A(S) A(R)	C/A(S) CS/PM(R)	A(S) A(R)	A(S) A(R)
	Tensile adhesion test temperature 23°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	CS	CS/PM	A/PC	PM	A/CS	A/CS/PM
Gravel with CEM1/GGBS	CS	CS	A	A,PM	A,CS	CS,PM
Lytag	A	A	A/PM	A/PM	A,/M	A
Repair surface	PM	A	A	A	A	A
Repair/Substrate Interface	CS(S) PM(R)	A(S) A(R)	A/PM(S) PM(R)	A(S) A(R)	A/PM(S) PM(R)	CS/PM(S) PM(R)
	Tensile adhesion test temperature 40°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	C	CS/PM	A/PC		CS	A/CS
Repair surface	PM	A	A	A	A/PM	PC
Repair/Substrate interface	C/CS(S) PM(R)	CS/PM(S) PM(R)	C/PM(S) PM(R)	A(S) A(R)	CS(S) PM(R)	PM(S) PM(R)

Key

C = failure within concrete

CS = failure at surface of concrete

PC = failure between primer and concrete

PM = failure between primer and membrane

A = failure of adhesive to membrane

(S) = on substrate

(R) = on repair material

5.3.3 System 3

All of the failure stresses exceeded the minimum requirements specified in Clause B4.2(d) of BD 47, even though many of the wet 14-day and 28-day, and the 3-day and 7-day slabs were not flame dried, but some individual results were near to the minimum required.

At a test temperature of -10°C, the mean failure stresses ranged from 59 to 111% of those for the corresponding 28-day dry slabs (Table 18). They were lowest for the 3-day slabs. The mean failure stresses were generally higher in the repair areas area and at the interface of the repair slabs than for the CEM1 slabs (Table 19).

At a test temperature of 23°C, the mean failure stresses of the CEM1 and CEM1/GGBS slabs ranged from 87% to 129% of those for the corresponding 28-day dry slabs. The mean failure stresses for the 3-day CEM1 and CEM1/GGBS slabs were higher than those for the 28-day dry slabs. The mean failure stresses for the Lytag slabs tended to be lower than those for the CEM1 and CEM1/GGBS slabs, apart from the 14-day slabs. The mean failure stresses were significantly higher for the 14-day wet slab (154%) and significantly lower (66%) for the 14-day dry slab. The mean failure stresses for the repair slabs tended to be slightly higher than those for the other types of slab, but that for the 28-day dry repair material was twice that for the other types.

At a test temperature of 40°C, the mean failure stresses ranged from 49 to 96% of those for the corresponding 28-day dry slabs. They tended to be higher for the CEM1 slabs than for the repair slabs.

The failure surfaces of the CEM1, CEM1/GGBS and Lytag slabs were mainly at the surface of the concrete, although there were failures of the primer to the concrete on some of the wet slabs (Table 20). Failures on the repair slabs tended to be between the primer and the repair material and at the surface of the concrete substrate. The repair material was smooth and not textured. The location of the failure surfaces did not vary greatly with the test temperature.

Table 18. System 3: Tensile adhesion test failure stresses as a percentage of dry 28-day results

Concrete mixtures	Mean failure stress as percentage of dry 28-day result (%)					
	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Tensile adhesion test temperature -10°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	66	92	101	85	100	104
Repair surface	60	95	75	81	100	65
Repair/Substrate interface	59	111	103	103	100	73
	Tensile adhesion test temperature 23°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	129	87	113	127	100	128
Gravel with CEM1/GGBS	127	113	112	92	100	103
Lytag	107	107	66	154	100	112
Repair surface	68	65	67	42	100	72
Repair/Substrate Interface	113	123	91	151	100	123
	Tensile adhesion test temperature 40°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	54	47	96	49	100	58
Repair surface	72	69	100	73	100	76
Repair/Substrate interface	75	60	44	79	100	57

Table 19. System 3: Tensile adhesion test failure stresses as a percentage of dry CEM1 28-day results

Concrete mixtures	Mean failure stress as percentage of dry 28-day result (%)					
	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Tensile adhesion test temperature -10°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	66	92	100	85	100	104
Repair surface	92	147	115	126	155	101
Repair/Substrate interface	68	127	118	118	115	84
	Tensile adhesion test temperature 23°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	129	87	113	127	100	128
Gravel with CEM1/GGBS	127	113	112	92	100	103
Lytag	107	107	66	154	100	112
Repair surface	68	65	67	42	100	72
Repair/Substrate Interface	113	123	91	151	100	123
	Tensile adhesion test temperature 40°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	54	47	96	49	100	58
Repair surface	56	54	70	57	78	60
Repair/Substrate interface	71	56	42	74	95	54

Table 20. System 3: Location of failure surfaces during tensile adhesion tests

Concrete mixtures	Location of failure surface Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Pull-off test temperature -10°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	CS	CS	CS	PC	CS	CS
Repair surface	PC	PC	CS	CS/PC	CS	PC
Repair/Substrate interface	CS(S) PC(R)	CS/PC(S) PC(R)	CS/PC(S) CS(R)	CS(S) C/CS/PC(R)	CS(S) C/CS/PC(R)	PC(S) PC(R)
	Pull-off test temperature 23°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	CS	CS	CS	PC	CS	CS
Gravel with CEM1/GGBS	CS	CS	CS	CS	CS	CS
Lytag	CS/PC	CS/PC	CS	CS	CS	CS/PC
Repair surface	PC/PM	PC	CS	PC	CS/PC	PC/PM
Repair/Substrate Interface	CS/PC(S) PC(R)	CS(S) PM(R)	CS(S) CS(R)	PC(S) CS/PC(R)	CS(S) PC(R)	CS(S) PC(R)
	Pull-off test temperature 40°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	CS	PC	CS	PC	CS	PC
Repair surface	PC	PM	PC	PC	PC	PC
Repair/Substrate interface	CS(S) PC(R)	CS/PC(S) PM(R)	PC(S) PC(R)	CS/PC(S) PC(R)	CS(S) PC(R)	CS/PC(S) PC(R)

Key

C = failure within concrete

CS = failure at surface of concrete

PC = failure between primer and concrete

PM = failure between primer and membrane

(S) = on substrate

(R) = on repair material

5.3.4 System 4

The failure stresses measured at -10°C exceeded the minimum values specified in Clause B4.2(d) of BD 47, but some and all of the mean failure stresses measured at 23°C and 40°C, respectively, did not.

At a test temperature of -10°C, the mean failure stresses for the CEM1 slabs ranged from 99% to 118% of those for the 28-day dry slab (Table 21), and they exceeded the minimum requirements specified in BD 47. The mean failure stresses for the repair material of the repair slabs were lower for the 28-day dry slab than for the other slabs, but the mean failure stress for the 28-day dry slab was the lowest measured at -10°C. The mean failure stresses for the interface between the repair material and the concrete substrate of the repair slabs ranged from 84% to 105%. Generally, the mean failure stresses were similar for the CEM1 and repair slabs, and they varied little with the age and curing regime of the slabs (Table 22).

At a test temperature of 23°C, the mean failure stresses for the CEM1 and CEM1/GGBS slabs ranged 77% to 105% of those for the corresponding 28-day dry slabs. The mean failure stresses were slightly higher for the 3-day slabs than for the 28-day dry slabs. The mean failure stresses were mainly higher for the CEM1 slabs than for the CEM1/GGBS slabs. The mean failures stresses for the Lytag and repair slabs ranged from 98 to 205% of those for the 28-day dry slabs; those for the 28-day dry slabs were lower than the minimum specified in BD 47. Generally, the mean failure stresses were lower for the Lytag and repair slabs than for the CEM1 slabs.

At a test temperature of 40°C, the mean failure stresses for the CEM1 slabs ranged from 104 to 162% of that for the 28-day dry slab, being highest for the 3-day slab. The mean failure stresses for the repair slab ranged from 59 to 107% of those for the 28-day dry slab. They tended to be higher for the CEM1 slabs than for the repair slabs, but the mean failure stresses measured on all of the slabs were below the minimum specified in BD 47. The variation in the mean failure stress with age and curing regime was small in terms of MPa, but larger percentage wise.

The failure surfaces of most slabs were at the interface between the sheet and the oxidised bitumen (Table 23). There were failures at the primer on some of the 3-day and 7-day Lytag and repair slabs at 23°C and 40°C, some 14-day wet CEM1 and Lytag slabs at 23°C, some 14-day wet and 28-day wet repair slabs at 23°C and 40°C, and the 14-day dry CEM1 slab at 23°C. The sheet failed in some tests on the 28-day dry repair slabs.

A typical failure surface at the interface between the membrane and the oxidised bitumen with voids present is shown in Figure 12. The failure surface shows some voids in the oxidised bitumen layer that reduced the contact area between the bitumen and the underside of the sheet membrane and, consequently, the failure stress. The spherical nature of the voids suggests that they were formed by out-gassing either during the application of the oxidised bitumen or during the hot sand test when solvent in the primer or moisture in the slab gasified. The surfaces of all slabs were dried; the wet and 3-day and 7-day slabs being dried more thoroughly than the dry slabs. The dry slabs were dried and fully waterproofed on the same day, so the solvent-based primer was left to cure for only two or three hours. Most of the other slabs were primed and left overnight before the oxidised bitumen and membrane were applied. The amount of primer that was taken up by the slabs and the time the primer was left to cure will have affected the amount of solvent present when the oxidised bitumen was applied. The different amount of out-gassing that resulted may have had an effect on the failure stresses and may explain why some of the lowest failure stresses were measured on the dry slabs.

Table 21. System 4: Tensile adhesion test failure stresses as a percentage of dry 28-day results

Concrete mixtures	Mean failure stress as percentage of dry 28-day result (%)					
	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Tensile adhesion test temperature -10°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	99	104	102	108	100	118
Repair surface	133	104	114	151	100	145
Repair/Substrate interface	91	84	90	95	100	105
	Tensile adhesion test temperature 23°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	105	99	105	77	100	87
Gravel with CEM1/GGBS	103	98	83	87	100	83
Lytag	123	98	104	168	100	152
Repair surface	205	189	169	156	100	132
Repair/Substrate Interface	152	146	161	145	100	120
	Tensile adhesion test temperature 40°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	162	112	140	134	100	104
Repair surface	93	91	59	81	100	87
Repair/Substrate interface	98	102	105	80	100	107

Table 22. System 4: Tensile adhesion test failure stresses as a percentage of dry CEM1 28-day results

Concrete mixtures	Mean failure stress as percentage of dry 28-day result (%)					
	Concrete age at time of application of waterproofing (days)					
	3	**7**	**14**		**28**	
	Tensile adhesion test temperature -10°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	99	104	102	108	100	118
Repair surface	110	86	94	124	82	120
Repair/Substrate interface	99	92	98	104	109	114
	Tensile adhesion test temperature 23°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	105	99	105	77	100	87
Gravel with CEM1/GGBS	92	88	74	78	89	74
Lytag	78	62	66	106	63	96
Repair surface	102	94	84	77	50	65
Repair/Substrate Interface	98	95	104	94	65	78
	Tensile adhesion test temperature 40°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	162	112	140	134	100	104
Repair surface	110	108	71	97	119	104
Repair/Substrate interface	119	124	128	97	121	130

Table 23. System 4: Location of failure surfaces during tensile adhesion tests

Concrete mixtures	Location of failure surface					
	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Pull-off test temperature -10°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	SB	SB	SB	SB	SB	SB
Repair surface	SB	SB	SB	SB	SB	SB
Repair/Substrate interface	SB(S) SB(R)	SB(S) SB(R)	SB(S) SB(R)	SB(S) SB(R)	SB(S) SB(R)	SB(S) SB(R)
	Pull-off test temperature 23°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	SB	SB	BP/PC	BP/SB	SB	SB
Gravel with CEM1/GGBS	SB	SB	SB	SB	SB	SB
Lytag	BP	PC	SB	BP/SB	SB	SB
Repair surface	PC	SB	SB	SB/S	SB	SB/PC
Repair/Substrate Interface	SB(S) PC/SB(R)	SB(S) PC(R)	SB(S) SB(R)	SB(S) SB/PC(R)	SB/S(S) SB(R)	SB(S) SB/PC(R)
	Pull-off test temperature 40°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	SB	SB	SB	SB	SB	SB
Repair surface	BP	SB	SB	SB	SB	SB
Repair/Substrate interface	SB(S) BP(R)	SB(S) BP/SB(R)	SB(S) SB(R)	SB(S) SB(R)	SB(S) SB(R)	SB(S) BP/SB(R)

Key

PC = failure between primer and concrete

BP = failure between oxidised bitumen and primer

SB = failure between sheet and oxidised bitumen

S = failure within sheet

Figure 12. Typical failure surface at the interface between the sheet and the oxidised bitumen showing voids at the interface

5.3.5 System 5

At a test temperature of -10°C, the mean failure stresses for the CEM1 and repair slabs ranged from 77% to 144% of those for the corresponding 28-day dry slabs (Table 24), and they exceeded the minimum requirements of BD 47. Generally, the mean failure stresses were similar for the CEM1 and repair slabs (Table 25), and the differences with the age and curing regime of the slabs were insignificant.

At a test temperature of 23°C, the mean failure stresses for the CEM1 and CEM1/GGBS slabs ranged from 106 to 166% of those for the corresponding 28-day dry slabs, and they exceeded the minimum requirements in BD 47 and in the current German Specification. The latter, TL/TP-BEL-EP, requires the tensile bond strength of the weakest interface of specimens comprising a concrete block and the waterproofing membrane to be not less than 0.7MPa at 8°C and 0.4MPa at 23°C. The mean failure stresses tended to be lower for the CEM1/GGBS slabs than the CEM1 slabs. However, those for the Lytag slabs were about half those for the CEM1 slabs, apart from the 3-day slabs for which the stresses were similar, and some were below the BD 47 requirements. The mean failures stresses for the repair slabs ranged from 80 to 130% of the corresponding 28-day dry slab values, and from 82 to 142% of those for the 28-day CEM1 dry slab.

At a test temperature of 40°C, the mean failure stresses measured on many slabs were below the minimum specified in BD 47. The mean failure stresses for the CEM1 slabs ranged from 129 to 176% of that for the 28-day dry slab. The mean failure stresses for the repair slabs ranged from 86 to 149% of the corresponding 28-day dry slab values, and they were similar to those measured on the CEM1 slabs.

Figure 13 shows a typical failure of the surface of the sheet and Figure 14 shows a failure of the sheet itself and the bond of the sheet to the bonding bitumen. The failure surfaces of most slabs tested at 23°C and 40°C were predominantly at the surface of the sheet (Table 26). These failures were dependent on the cohesive failure of the sheet material and are probably why the mean failure stresses did not vary greatly with the age and curing regime of the slabs. Some of the failure surfaces on the Lytag specimens were at the bonding bitumen, and the bond of the bitumen to the primer and the sheet may have been affected by the age and moisture content of the slabs and resulted in the lower mean failure stresses measured on these slabs.

The failure surfaces of the slabs tested at 40°C were predominantly within the concrete, at the interface between the sheet and the bonding bitumen, within the sheet and at the surface of the sheet. There were no failures of the primer to the concrete, so again this may be why the failure stresses did not vary greatly with the age and curing regime of the slabs.

Because the sheet membrane was not overlaid with Güssasphalt, any changes in the membrane that would normally occur during the application of Güssasphalt on bridges were not taken into account in the tests.

Table 24. System 5: tensile adhesion test failure stresses as a percentage of dry 28-day results

Concrete mixtures	**Mean failure stress as percentage of dry 28-day result (%)**					
	Concrete age at time of application of waterproofing (days)					
	3	**7**	**14**		**28**	
	Tensile adhesion test temperature -10°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	120	118	124	115	100	144
Repair surface	93	119	97	77	100	94
Repair/Substrate interface	109	109	96	91	100	113
	Tensile adhesion test temperature 23°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	117	128	115	106	100	110
Gravel with CEM1/GGBS	166	129	152	126	100	136
Lytag	219	104	118	64	100	117
Repair surface	118	119	123	80	100	109
Repair/Substrate Interface	114	102	130	92	100	121
	Tensile adhesion test temperature 40°C					
			Dry	**Wet**	**Dry**	**Wet**
Gravel with CEM1	149	176	159	144	100	129
Repair surface	124	135	131	149	100	122
Repair/Substrate interface	108	86	104	134	100	93

Table 25. System 5: tensile adhesion test failure stresses as a percentage of dry CEM1 28-day results

Concrete mixtures	Mean failure stress as percentage of dry 28-day result (%)					
	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Tensile adhesion test temperature -10°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	120	118	124	115	100	144
Repair surface	123	157	128	101	132	124
Repair/Substrate interface	120	120	107	100	110	125
	Tensile adhesion test temperature 23°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	117	128	115	106	100	110
Gravel with CEM1/GGBS	128	99	117	97	77	105
Lytag	119	56	64	35	54	63
Repair surface	121	121	125	82	102	111
Repair/Substrate Interface	134	120	153	108	117	142
	Tensile adhesion test temperature 40°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	149	176	159	144	100	129
Repair surface	131	142	138	158	106	129
Repair/Substrate interface	148	117	142	183	137	127

Table 26. System 5: location of failure surfaces during tensile adhesion tests

Concrete mixtures	Location of failure surface					
	Concrete age at time of application of waterproofing (days)					
	3	7	14		28	
	Pull-off test temperature -10°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	SS	SB/S	SS/SB	SS/SB/A	SS/SB	SS
Repair surface	A	SS	SS/S	SB	SS/A	SS/S
Repair/Substrate interface	C/SB(S) C/S(R)	SS(S) SS(R)	C/S(S) C/S(R)	SS/SB(S) SS/BP(R)	C(S) C(R)	SS(S) SS(R)
	Pull-off test temperature 23°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	SS	SS	SS	SS	SS	SS
Gravel with CEM1/GGBS	SS	SS	SS	SS	SS	SS
Lytag	BP/SS	SB	SS/SB	SS/SB	SS	SS/SB
Repair surface	SS	SS	SS	SB/SS	SS	S
Repair/Substrate Interface	SS(S) SS(R)	SS(S) SS(R)	SS(S) SS(R)	SS(S) SS(R)	SS(S) SS(R)	SS/S(S) SS/S(R)
	Pull-off test temperature 40°C					
			Dry	Wet	Dry	Wet
Gravel with CEM1	SS/SB	S/SS	SS	SS/S	S	SS/S
Repair surface	SS	SS	SS	SS	SS/S	SS
Repair/Substrate interface	SS/S(S) SS/S/SB(R)	SS(S) SS(R)	SS(S) SS(R)	SS(S) SS(R)	SS/S(S) SS/S(R)	SS/S(S) SS/S(R)

Key

C = failure within concrete

BP = failure between bonding bitumen and primer

SB = failure between sheet and bonding bitumen

S = failure within sheet

SS = failure at sheet surface

A = Adhesion failure (adhesive to sheet / adhesive to dolly)

Figure 13. Typical failure at the surface of the sheet

Figure 14. Failure of the sheet itself and of the bond of the sheet to the bonding bitumen

6 Discussion

6.1 Observations during the application of the systems

The surfaces of the slabs for Systems 1 to 4 were wire brushed whereas those for System 5 were grit blasted. The surface of the repair material of the repair slabs of System 1 to 4 was not textured (see Section 4.2.3.3) and higher tensile adhesion values may have been recorded for some of the systems if they had more texture.

The surface moisture condition was assessed visually for the application of Systems 1, 3, 4 and 5, as in accordance with standard site practice. Only the wetter looking slabs of Systems 1 and 3 were flame dried. Generally, only the dry slabs of Systems 4 and 5 were not flame dried.

The surface moisture content was measured by moisture meter before the application of System 2. Some slabs required considerable flame drying to achieve the required surface moisture content, although the drying reduced the bulk moisture content of most slabs by only a small amount.

The moisture meter purchased by TRL for the test programme gave unreliable results and was therefore totally ineffective. The moisture meter used by the supplier of System 2 has been used successfully on bridges. It would be inappropriate to use another type of moisture meter to determine when it would be appropriate to apply System 2 without its accuracy being verified and without ensuring that the required tensile adhesion can be achieved at or below the limiting surface moisture content.

The primer of System 4 took longer to cure than the primers of the spray applied systems, although it is possible that some of the low tensile adhesion values for the spray applied systems occurred because the primer had not been left long enough to cure. Curing time on bridges is normally longer than the little over an hour that was the case in these tests. The primer of System 5 was left to cure at 23ºC for about 24 hours, although the curing time may be less at that or higher temperatures, or longer at a lower temperatures.

6.2 Performance of the systems

The results from these tests show clear trends that are indicative of the performance of the waterproofing systems when applied to concrete at ages up to 28 days. However, it should be noted that in order to carry out a full statistical analysis of all the variables tested to determine the significance of these trends, it would have been necessary to include replications for each variable at the different levels.

At a test temperature of -10ºC, the tensile adhesion of all five systems exceeded the minimum specified in BD 47 (0.3MPa) by a considerable margin. For the spray applied systems, the tensile adhesion was higher for the repair slabs than for the CEM1 slabs. The tensile adhesion varied little with the age and curing regime of the slabs for System 1, but it tended to be lower for the 3-day slabs than for the older slabs for Systems 2 and 3. For the sheet system, the tensile adhesion was similar for both types of slab and varied little with the age and curing regime of the concrete.

At a test temperature of 23ºC, the tensile adhesion of the spray applied systems exceeded the minimum specified in BD 47 (0.3MPa) - by a considerable margin for System 1 and by a considerable margin for all but one or two tests for Systems 2 and 3. The tensile adhesion tended to be higher for the repair slabs than for the CEM1 slabs, and tended to be higher for the CEM1 slabs than for the CEM1/GGBS slabs. For Systems 1 and 3, the tensile adhesion tended to be higher for the CEM1 slabs than the Lytag slabs, but the opposite was found for System 2. The age and curing regime of the slabs did not have an adverse effect on the tensile adhesion of Systems 1 and 3; the tensile adhesion of the 28-day dry slabs was generally lower than that of the other slabs. The tensile adhesion was generally lower for the 3-day slabs than for the others for System 2.

At a test temperature of 23ºC, the tensile adhesion of both sheet systems generally exceeded the minimum specified in BD 47 for the CEM1 and CEM1/GGBS slabs, and for the repair slabs of System 5. Some values below the minimum were measured on the Lytag slabs and on the repair slabs of System 4. The tensile adhesion was generally higher for the CEM1 slabs than for the CEM1/GGBS slabs for both sheet systems, and higher for the repair slabs than for the CEM1 slabs for System 5. The tensile adhesion was higher for the CEM1 slabs than the Lytag slabs, except for the 3-day slabs of System 5 when similar values were measured. The tensile adhesion for the 3-day slabs was higher than that for the other slabs for both sheet systems for all four types of slab. Apart from the 3-day slabs, the tensile adhesion varied little by the age and curing regime of the slabs.

At a test temperature of 40ºC, the tensile adhesion of the spray applied systems exceeded the minimum specified in BD 47 (0.2MPa) by a considerable margin. The tensile adhesion tended to be higher for the CEM1 slabs than for the repair slabs for Systems 1 and 3, but the opposite was the case for the repair material of the repair slabs of System 2. The tensile adhesion varied little with the age and curing regime of the slabs for System 1, but it tended to be higher for the 14-day and 28-day dry slabs than for the other slabs for System 3. For System 2, the tensile adhesion was lower for the 3-day slabs and the 28-day wet slab than for the others, but these values were higher than those for System 3. Also, the values for the other slabs for System 2 were generally higher than those for Systems 1 and 3. Furthermore, the variation in the tensile adhesion with temperature was less for System 2 than for the other systems.

At a test temperature of 40ºC, the tensile adhesion of the sheet systems was generally below the minimum specified in BD 47. The tensile adhesion tended to be higher for the CEM1 slabs than for the repair slabs and it varied little with the age and curing regime of the slabs. The failure surfaces of System 4 and System 5 were, respectively, predominantly at the interface between the oxidised bitumen and the sheet and within the sheet.

Higher tensile adhesion values may have been measured if System 4 had been overlaid with surfacing that had been rolled, and if System 5 had been overlaid with Güssasphalt at 240ºC.

Although the tensile adhesion was high for the repair slabs in most cases, it is likely that higher values would have been measured for Systems 1, 2 and 3 if the repair material had been textured by grit blasting as was the case for System 5.

6.3 Comparison of the findings with previous research

Other researchers have found that pin/blow holes and blisters are most likely to occur in waterproofing systems applied to areas where the surface of the concrete is wet. Also, it has been found that the risk of pin holing is reduced if the bulk moisture content is greater than 4.5%. Since the surfaces of the slabs were dried prior to the application of the waterproofing system, and the bulk moisture content generally exceeded 4.5%, the absence of pin/blow holes and blisters is consistent with the findings of others.

It has been estimated that a gas pressure of 0.3MPa (the minimum tensile adhesion specified in BD47 at -10ºC and 23ºC) would be generated under a waterproofing membrane if the temperature of the concrete increased by about 115ºC (e.g. an increase from 20ºC to 135ºC). This temperature increase could arise when a waterproofing system is overlaid with hot asphalt. However, the tensile adhesion of the systems tested decreased with increasing temperature, although less so for System 2, but it could have been considerably less than 0.3MPa during the hot sand conditioning test that simulated the application of surfacing material.

The primer of System 5 is used specifically to prevent out-gassing, and the primers of the spray applied systems appear to have had a similar effect as evidenced by the high tensile adhesion measured at -10ºC. There was evidence of out-gassing due to the solvent based primer of System 4, but the main reason for the low tensile adhesion values measured on at 40ºC on Systems 4 and 5 appears to be due to the properties of the waterproofing systems themselves, rather than out-gassing.

Previous research has measured the tensile adhesion of waterproofing systems applied to different types of C40 concrete, including mixtures with GGBS, of different moisture content and age ranging from 7 to 28 days. The surfaces were allowed to dry naturally or artificially for application. The adhesion varied little with the bulk moisture content of the slabs when measured at 7 days and 6 months after application of the waterproofing system. Other tests have found no effect of concrete age for sheet systems when applied to slabs aged from 7 days to one year, and an increase in adhesion with age for spray applied systems. The findings are again consistent with those from these tests. Furthermore, the previous research indicates that the tensile adhesion does not reduce over time when the waterproofing system is applied to concrete aged from 7 to 28 days.

It is concluded from the tests reported here and previous research that the performance of waterproofing systems should not be adversely affected by application to concrete aged 7 days or more, provided they are applied in the same way as during these tests. The test slabs were waterproofed soon after they were surface dried so there was little if any time for moisture to migrate from the bulk of the concrete material back to the surface after drying. Therefore, the time delay between surface drying and priming should also be kept to a minimum on bridges to reduce the risk of unsatisfactory performance.

The waterproofing system has blistered on some bridges several years after they were waterproofed. It appears that in hot weather, vapour pressures have been generated under the waterproofing membrane that have been sufficient to cause ‘bumps’ to be formed in the surface course when the stiffness of the asphalt layers has decreased at high temperatures. It is thought that such blisters are formed initially where water, or solvents from solvent-based primers below the membrane are vaporised during surfacing. The size of the blisters is, presumably, limited by the dead weight of the surfacing and compaction forces until solar radiation increases the pressure within the blister and softens the asphalt. There may be an increased risk of blisters forming in this way when concrete is waterproofed at an early age when the moisture content is higher. However, the risk is considered to be low if there is adequate surface drying so that the initial bond of the waterproofing system to the concrete is good.

7 Conclusions

1. The time required to apply the five waterproofing systems to the slabs varied greatly. The spray applied systems were applied within a few hours, whereas the time required to cure the primers of the sheet systems delayed the installation of their membranes.
2. The waterproofing systems were not applied before the surfaces were deemed by the applicators to be sufficiently dry. The surface moisture content of the System 2 slabs was measured using a moisture meter, whereas the other slabs were assessed visually. The slabs were flame dried to achieve the appropriate surface condition. More drying was required for System 2 than for the other systems.
3. No pin/blow holes or blisters were evident on any of the slabs of any system at any stage throughout the test programme.
4. At a test temperature of -10ºC, the tensile adhesion of all five systems exceeded the minimum specified in BD 47 (0.3MPa) by a considerable margin.
5. At a test temperature of 23ºC, the tensile adhesion of the spray applied systems exceeded the minimum specified in BD 47 (0.3MPa) - by a considerable margin for System 1 and for all but one or two tests for Systems 2 and 3. The tensile adhesion of the sheet systems generally exceeded the minimum specified in BD 47 for the CEM1 and CEM1/GGBS slabs, and for the repair slabs for System 5. Some values below the minimum were measured on the Lytag slabs and on the repair slabs for System 4.
6. At a test temperature of 40ºC, the tensile adhesion of the spray applied systems exceeded the minimum specified in BD 47 (0.2MPa) by a considerable margin, but the tensile adhesion of the sheet systems was mainly below the minimum specified.
7. The tensile adhesion was different for the different substrates. The substrate which gave the highest tensile adhesion varied with the system, the test temperature and the age and curing regime. For most systems and test temperatures, the tensile adhesion varied little with the age and curing regime of the slabs. Some lower tensile adhesion values were measured on some of the 3-day slabs and wet slabs for some systems.
8. Higher tensile adhesion values may have been measured if System 4 had been overlaid with surfacing that had been rolled, and if System 5 had been overlaid with Güssasphalt at 240ºC - an integral part of this system in Germany.
9. Generally, the findings from these tests were consistent with the findings from other studies.
10. Taking all factors into account, it is concluded that the performance of waterproofing systems on bridges should not be adversely affected by application to concrete aged 7 days or more, provided they are applied in the same way as during the tests reported here. In particular, the time between surface drying and the application of the primer should be as short as possible so that any moisture that may migrate from the bulk of the concrete material back to the surface is minimal.
11. Pull-off tests should be conducted on site after the installation of the membrane and before surfacing to confirm that the condition and dryness of the surface of the concrete was sufficient to give adequate initial tensile adhesion of the waterproofing system to the concrete.

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