Sustainable, “green” solutions for concrete pavement rehabilitation - a feasibility (pilot) study

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SUSTAINABLE, "GREEN" SOLUTIONS FOR CONCRETE PAVEMENT REHABILITATION. _A feasibility (pilot) study.

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ABSTRACT

Thin bonded asphalt and thicker, unbonded concrete overlays for concrete pavements can offer some benefits to worn concrete pavements such as restore skid resistance and riding quality as well as reduce routine maintenance. Continuously Reinforced Bonded Concrete Overlays (CRBCO) can offer all the above plus a '*greener*' and sustainable solution to the problem of rigid road and airfield repairs, because they make use of the remaining strength of the worn pavement. Hence, they can offer both, real savings as well as environmental benefits over the wholesale demolition, removal and complete reconstruction of the existing pavement. This paper is the introduction of a research study dealing with the development of CRBCO as a new material and method of construction. It demonstrates that it is possible to go for a wholesale replacement of the traditional steel reinforcement with new, innovative, corrosion free, easier and faster to apply synthetic alternatives and at the same time make a positive contribution to flexural resistance, crack control, shear and bond strength of the rehabilitated pavement. Finally, it stresses the need for further research for the new material and method to become widely applicable. It is hoped that the advent of more high-quality, high-tensile strength concretes and techniques, such as high-speed paving and roller compaction, combined with careful attention to all the design requirements will enable pavement engineers to exploit the advantages in terms of economy, convenience and long maintenance-free, greener life which CRBCO could offer in the future.

KEYWORDS: Sustainability, Concrete pavements, overlays, synthetic reinforcement, roads & highways, airports.

1. INTRODUCTION

The need to implement sustainable development practice in all sectors of construction has been widely recognised and, in particular, improvements in the approach to the design, , construction, operation and rehabilitation of major transport infrastructure projects have already been proposed. Some have also been implemented *[Britpave 2000]*. Whole life costing for highway maintenance work in the UK was pioneered in the 1980's. For example, environmental, social and financial needs have been carefully balanced for bridges and access structures and a minimum design life of 100 years or more is now typical. However, despite these advances, UK, in comparison to other economically advanced nations, has not in general embraced sustainability and whole life costing considerations for the highway pavements due to under investment and short term non-sustainable solutions *[The Highways Agency & Britpave 2003]*.

The later may also be due to the reluctance of pavement engineers to incorporate new and innovative solutions into new pavements. Hence, existing analytical and design methods for new pavements are based on simplified models that do not always represent the actual conditions satisfactorily. Also, re-design of pavements to be repaired, is usually based on a practical (mechanistic) approach, relying on past experience and previous, long-term observations and can be costly as it does not take advantage of the remaining life of the worn pavement *[Ullidtz 1987]*. In fact, the increasing use of heavier and more complex types of loads generated by vehicles and aircraft, emphasises the urgent need for improved design methods for new pavements and for better, more environmentally friendly ways of rehabilitating existing roads and airport runways with the emphasis on sustainability. It has now been widely accepted that complete removal and replacement of a worn pavement is a waste of an existing asset, environmentally unfriendly and unsustainable, and should only be considered as a last resort.

2. DEFECTS & WEAKNESSES IN CONCRETE PAVEMENT OVERLAYS

The benefits of structurally improved BCO have now been recognised but not many applications have been successful, due to several problems still waiting to be resolved *[Hughes 2003]*. These problems and their associated modes of failure are briefly mentioned below:

2.1 Sub-base and Sub-grade severe decaying.

Subbase and/or subgrade deterioration is a common mode of failure usually associated with drainage problems. If shear transfer across a crack (or movement joint) in the worn pavement has been lost or seriously impaired, the subbase and subgrade reaction on either side will also be inadequate. It is essential therefore that serious deficiencies in the subgrade reaction are eliminated by employing either crack-and-seat or concrete injection techniques, before any overlays are applied.

2.2 Shear failure across old cracks and transfer to BCO.

The shear resistance across a long established crack in a warn pavement can sometimes start to deteriorate rapidly even if little loss in shear transfer is evident. The minimum depth for the overlay should therefore be established, by considering only the shear resistance of the uncracked BCO on a diagonal plane. Hence, if the maximum design cracks in the BCO can be restricted to acceptable limits, the shear resistance of the cracked BCO above an existing old pavement crack should be greater than, or equal to, the shear resistance on a diagonal plane *[Hughes 2006]*.

$$\tau_{crack} \geq \tau_{dia\ plane}, \quad if : crackwidth \rightarrow 0 \qquad (1)$$

2.3 Bond failure between overlay (new) and old pavement.

Bond breaking between the old, worn out pavement and the new overlay is another common mode of failure. It has been demonstrated that this is not the result of the horizontal stresses generated by vehicle braking forces alone. Rather, it is the combination of the latter, plus other factors such as flexural loads, environmental effects (thermal gradients) and stress concentrations at defects *[Lau et al 1994]*.

2.4 Reflection cracking in the BCO

These are existing cracks in the old pavement, finding their way up the surface of new overlay due to continuous positive and negative rotations of the two portions of pavement under traffic and other loads. Reflection cracking cannot be avoided, hence must be suitably resisted by restricting the crack width in the BCO. This, in turn, can be achieved by restricting the angle of rotation of the crack, pivoting about the reinforcement of the overlaid pavement *[Hughes 2003]*.

2.5 Flexural failure

BCO, although of high quality concrete with a higher bond strength than normal, are still a brittle material and therefore liable to fracture without yielding. Hence, another possible mode of failure is that of flexure. The only way to avoid this kind of failure is by allowing the overlay to crack, but control cracking by introducing the right amount of continuous reinforcement. Hence provide the cracked pavement similar resistance to that of the uncracked pavement.

2.6 Delamination at discontinuities

Delamination is a mode of failure occurring mainly at discontinuities such as edges and movement joints where stress concentrations can be high. It is due to the combined effect of thermal and traffic loads. It can also occur at the ends or sides of the pavement, if no end restraint and/or continuous transverse and longitudinal reinforcement is present.

3. NOTES FOR SUCCESSFUL STRUCTURAL PERFORMANCE OF BCO.

The concrete in the overlay should be of high-quality, preferably polymer modified and the bond strength at the interface should be higher than the tensile strength of the existing concrete (as interface stresses are of shearing nature a higher bond should be achievable) *[Karadelis et al 2003]*. Good bond strength and good preparation of the existing pavement surface is absolutely essential. Delatte et al *[1998]* noted from their very successful full-scale test sections in El Paso, Texas that rougher surface preparation substantially improved performance. A mean roughness of 1.30mm was observed for the shot-blasted section and an even better 1.71mm for hydrocleaning. They found that cold milling can cause cracking below the prepared surface and should be avoided.

Delamination tends to occur due to thermal cracks first at stress concentrations at the interface and to other discontinuities in the BCO (eg edges and movement joints). The continuous reinforcement in the BCO greatly restrains any possible curling and warping in the pavement at cracks if the transverse as well as the longitudinal reinforcement is adequate. Vertical restraint at all transverse expansion joints or other discontinuities in BCO pavements by either a wide flange beam joint or ground beam anchorage has been proposed *[Gregory 1984], [Garnham 1989]*. However, this may sound as an old fashion solution and therefore other, more economical and sustainable solutions should be sought.

Reflection cracking in the BCO above all live cracks in the worn pavement subjected to flexure is inevitable. It is therefore vital that the rotation angle at the 'hinge' due to the crack in the semi-rigid pavement is strictly limited by restricting the crack width in the BCO. When the BCO cracks the flexural strength, stiffness and fatigue life, as well as the shear strength must remain <u>at least</u> adequate. The finer the crack, the higher the flexural stiffness and the higher the long-term fatigue life. However, decreasing the design crack width increases the cost of the reinforcement (smaller diameters and/or increased amounts) but maintains sufficient overall pavement stiffness to ensure adequate preservation of the subgrade. Obtaining data for the optimum design crack widths to use for an ideal balance between an adequately extended life and economy is a most crucial objective of the proposed research.

4. EXPERIMENTAL, PILOT STUDY. Aim and Objectives

At Coventry, we have been experimenting for some time with a polymer modified concrete and with the help of our Industrial Partners we have been able to develop a material with superior properties such as high compressive and tensile strengths of the order of 90MPa and 12MPa respectively and also good bonding characteristics and promising resistance to delamination. However, if this new concrete is intended for use as a pavement overlay it has to have additional special properties in order to minimise costs. For instance, it has to be easily applicable, preferably by an asphalt paver and pressed by a vibrating roller. That is, it has to have the properties of high strength concrete and the versatility, ease and speed of application of asphalt *[Karadelis et al 2003]*. A major drawback to the later and a parameter closely associated with costs is the conventional steel reinforcement as it includes design, purchasing, transportation and placement costs. This has to be replaced with alternatives if a more economical and faster solution, part of the overall sustainable design to pavement rehabilitation is sought.

Therefore, based on the problems listed in Section 2, above, a pilot study was planned aiming to investigate the following:

a. the possibility to replace the main steel reinforcement with a more suitable material, examine the mode of failure of a series of specimens and propose solutions to enhance the flexural resistance of the BCO pavement.
b. the tendency of new concrete (overlays) to break away (de-bond) from the old pavement (ie: study the mechanism of delamination) and to find ways to quantify and control the delamination process.
c. the problem of delamination at the edges and corners due to curling and warping generated by thermal stresses.

4.1 Preliminary work

All preparatory work such as the design and manufacturing of the necessary formwork was carried out at the University's workshops. Marine plywood was used to construct a series of prismatic moulds in order to produce the appropriate small beam and slab specimens for testing. These moulds were transported to Aggregate Industries laboratories and their recently acquired facilities were used to design, mix and cast the polymer modified concrete. Preliminary, basic results such as cube strengths were extracted and sent back to University together with a number of specimens for further testing. An indicative table is shown below (Table 1).

As it was mentioned earlier, a major drawback of the concrete roads compared against their asphalt counterparts is the very slow speed of construction of the former. This is owned to the time taken for the reinforcement to be placed and for the concrete to develop its full strength (Figure 1).

Hence, alternatives have to be found. First, the advantage of using polymeric concrete for road paving is that it develops adequate strength and can be passed to traffic within the first three days of its life. Second, a new type of reinforcement has been introduced, that of a synthetic (modified polyolefin) reinforcing fibre, which has a contoured surface similar to steel to maximise bond, a high tensile strength of up to 550 MPa and the trade name of 'BarChip' *[Bernard S 1999]*.

Table 1 Indicative cube strengths for different types of concrete mixes.

Trial Mix & Comments	Strength N/mm^2	Density Kg/m^3	Strength N/mm^2	Density Kg/m^3
	7 Days		28 Days	
TM06/113	36.54	2338	46.88	2330
Plain Concrete			43.33	2327
			46.87	2334
MEAN	36.54	2338	45.69	2330
TM06/114 F1	66.3	2297	74.59	2293
Polymer. Mod.			72.73	2299
Concrete			73.44	2294
MEAN	66.3	2297	73.59	2295
TM06/114 F2	64.52	2298	76.02	2309
Poly. Concrete +			67.26	2303
Fibres			76.09	2302
MEAN	64.52	2298	76.06	2306
TM06117	46.15	2292	57.98	2281
Poly. Concrete			62.45	2274
+Fibres+H_2O			66.59	2291
MEAN	46.15	2292	62.34	2282

A wholesale replacement of steel reinforcement is therefore sought, by providing a 'cocktail' of synthetic fibres in the mix and a mesh as main and secondary reinforcement, in an effort to keep construction time and costs as low as possible.

Figure 1 Rigid pavement steel reinforcement and dowel bars detail.

Figure 2(a) below shows a better performance of BarChip fibre reinforced concrete compared to its steel rivals. Specifications of the materials and details are shown in Table 2. Figure 2(b) shows a representative Load v Extension curve taken from tensile tests on Barchip 'wire'. The maximum tensile load recorded before failure was 259 N. The mean diameter of Barchip was recorded as 1.003mm. Hence, its tensile strength was estimated to be 327.43 Nmm^{-2} (MPa). Note that engineering stress (strength) does not give a true indication of the deformation characteristics of a ductile material because it is based entirely on the original dimensions of the specimen, whereas it is known that these dimensions change continuously during the test. However, for the present, pilot study, it was considered to be acceptable.

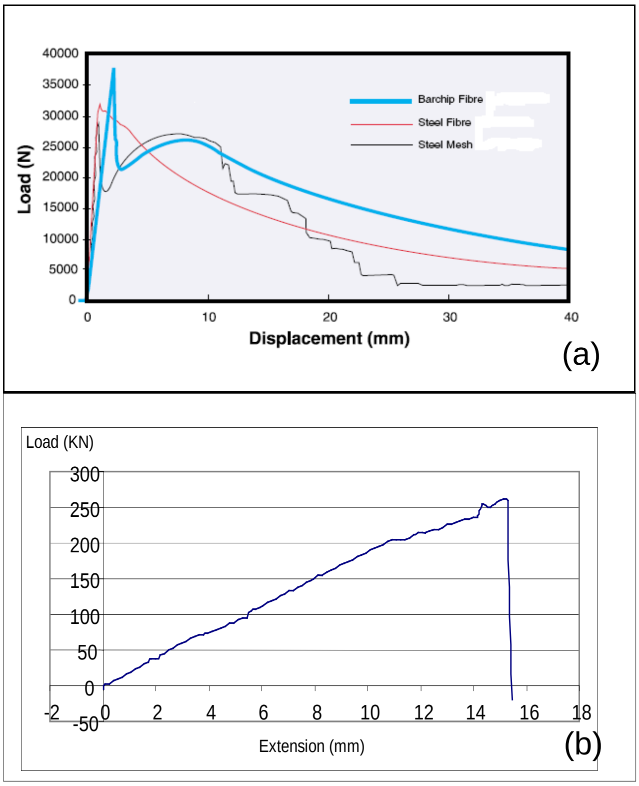


Figure 2. (a) Comparison between Barchip fibres, steel fibres and steel mesh. *(Bernard S 1999).* (b) Direct tension test. Load v Extension curve for Barchip.

Table 2 Materials and Specifications

Specimen	Description
Barchip synthetic fibre. Length =48 mm	Dosage rate: 10 kgm^{-3}
Steel fibre. High performance, hooked end	Dosage rate: 40 kgm^{-3}
Steel mesh. Type F41	4mm wire @ 100mm c/s

4.2 Tests with BarChip as main reinforcement

A series of laboratory tests were carried out on small, prismatic, polymer modified, concrete beams (360x60x60 mm) reinforced with BarChips to assess their performance. Similar plain concrete prisms as well as prisms with 1.00mm diameter steel wire reinforcement are also plotted alongside, for comparison. The "BarChip ratio" obtained was much lower than the corresponding minimum steel ratio allowed by BS8110 and Eurocode 2. However, the point was made. A sample of the results is shown in Figures 3 & 4.

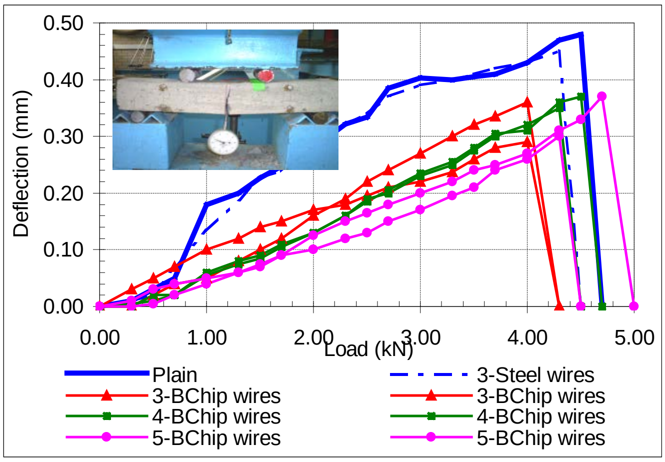


Figure 3. Flexural tests. Load v Deflection. Comparison between beams with different amount of BarChip reinforcement.

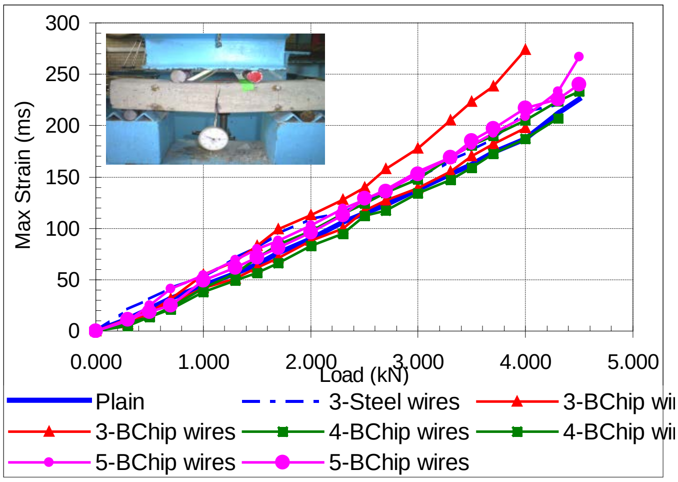


Figure 4. Flexural tests. Load v Strain. Comparison between beams with different amount of BarChip reinforcement.

It is recognised that the results are preliminary and that more tests are needed for confidence to increase. However, indications are that replacing conventional with continuous synthetic reinforcement may be possible, with substantial reductions in deflection and strain achieved by increasing the number of BarChip 'wires'. That is, BarChip reinforcement can replace steel successfully and make a contribution to flexural resistance and bond strength. The later should also be more effective in controlling minor cracks as BarChip can be strong enough to crack the immature concrete. That is, if the BarChip ratio exceeds some Critical ratio still to be defined.

4.3 Assessing the bond between old pavement and new overlay.

A series of PC concrete prisms were cast in special moulds blocked at 45^0. The 45^0 surfaces were treated to different degrees of roughness, according to the number of times a wire brush was passed over, as follows: 0, 10, 20, 30, 40, 50 and 60-passes. After fully setting, polymeric concrete was added and a bond was created between the two inclined surfaces. The prisms were subjected to compression and the load to failure was recorded. Table 3 summarises the tests and shows two indicative types of failure. It is obvious from this table that a good bond can be achieved relatively easily. However, bond is limited to excess brushing, linked to high exposure of aggregate and damaging of the bonding surface.

Table 3. Summary of 45^0 shear tests

Beam No.	No of Brush-passes	Max load P_{max} [kN]	Mode of Failure
1	0	?	Debonded during transportation.
2	10	?	Debonded at very low load.
3	20	109.6	Debonded
4	30	111.4 93.6	Bond failure Bond failure
5	40	147.8 106.9	Bond failure Bond failure
6	50	130.8	Compression failure
7	60	57.4 71.2	Premature failure Premature failure

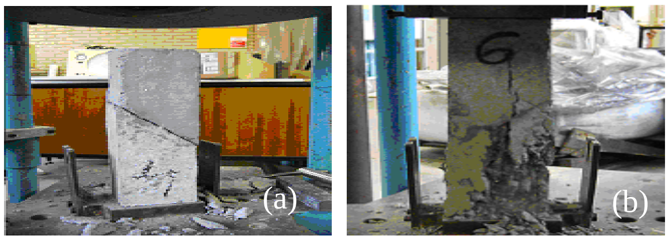


Figure 5. Bond (a) and Compression (b) failure.

Additionally, a series of flexural tests were carried out on beam specimens made of old PC concrete and covered with a layer of polymer modified concrete, in order to estimate the horizontal shear at the interface. Dimensions and specifications were as per Figure 6, below.

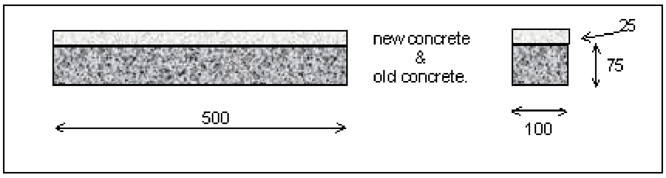
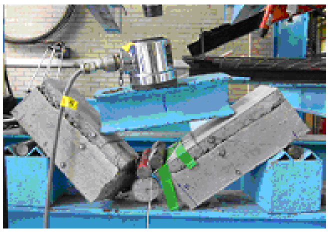


Figure 6. Beam specimens made of old and new concrete and their dimensions.

As before, in order to create a rough surface, the top face of the old concrete was treated with a wire brush prior to full setting, by applying 50, 100, 150, 200 and 250 brush passes. The treated surface was vacuum cleaned and a 25mm layer of polymeric concrete was applied. Three pairs of demec points were attached at the vertical face of the 'composite' beam, at distances 10mm, 60mm, and 90mm from the bottom and four point loading tests were carried out. Table 4 summarises the tests and shows the two modes of failure.

Table 4. Summary of flexural tests.

Batch Beam No.	No of Brush-passes	Max load P_{max} [kN]	Mode of Failure
1	0	?	Delamination during transportation
2	50	8.5	Flexural
3	100	9.0	Flexural
4	150	9.0	Flexural
5	200	8.5	Flexural
6	250	8.5	Delamination due to loose aggregate



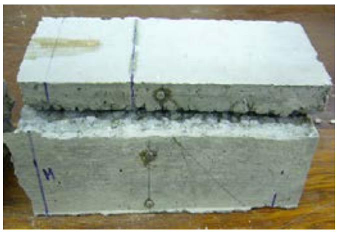


Figure 7. Flexural failure (a) and delamination (b)

Unfortunately, due to the relatively low number of tests carried out it was not possible to draw tangible and credible conclusions by studying Table 4, above.

However, it can be stated from the same table that bond strength increases with number of brush passes (rougher surface), as expected. There is however a limit to the bond strength achieved, after which the strength decreases. In this case this could be due to coarse aggregate dislocation and loosening from the parent material; hence creating a *plane of weakness* between the two concretes.

The strain distribution per load increment across the depth of the beams, at midspan, was also plotted. Some indicative results are shown in Figure 8, below. Whole load increments are shown only, for clarity. The position of Neutral Axis was estimated from the graph to be at approximately 47.5mm above the bottom of the beam; slightly lower than halfway up or down, attributed to the influence of the polymeric concrete layer.

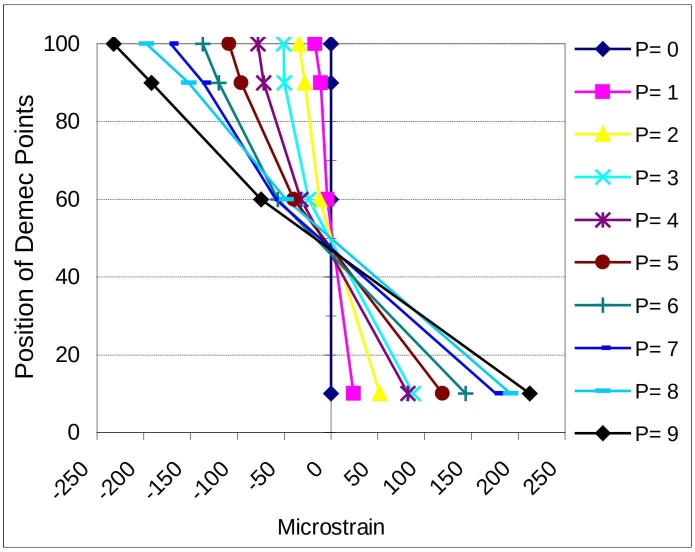


Figure 8. Strain distribution per load increment at midspan, across the depth of Beam 2F.

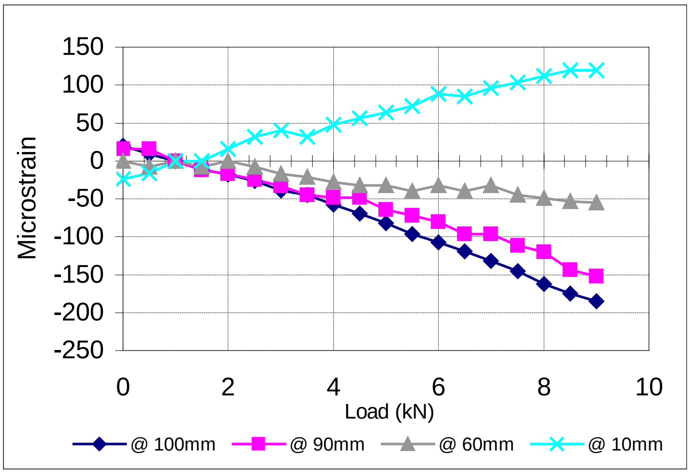


Figure 9 Strain v Load at midspan across the depth of Beam 4F

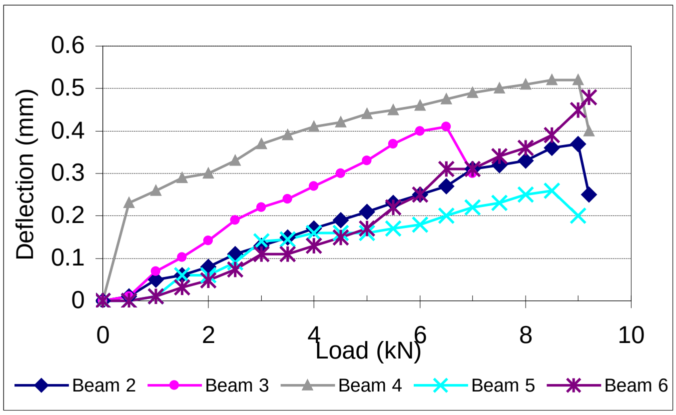


Figure 10. Variation of Deflection with Load. Beams 2F – 6F.

Figure 9 shows the variation of strain with load measured at midspan. Marker labelled '@ 100mm', shows readings from the electrical resistance strain gauge placed on top, whereas the rest show readings taken by the mechanical strain gauge. A typical concrete-in-flexure behaviour has been demonstrated with promises of good bond strength.

Figure 10 shows the variation of maximum deflection (at midspan) with load for Beams 2F (50 brush-passes) to 6F (250 brush-passes). The familiar trend continuous as beams with rougher interface between 'old' and polymeric concrete tend to behave as 'composites', withstand more load and undergo larger deflections.

4.4 *Curling and Warping at the edges and corners.*

These tests incorporated a series of small concrete slabs (300x300x30 mm) , approximating their behaviour under thermal and traffic loads and establishing their mode and mechanism of failure. These slabs were reinforced with both BarChip fibres and wires as shown in Figure 12(b).

Figure 11. Warping failure

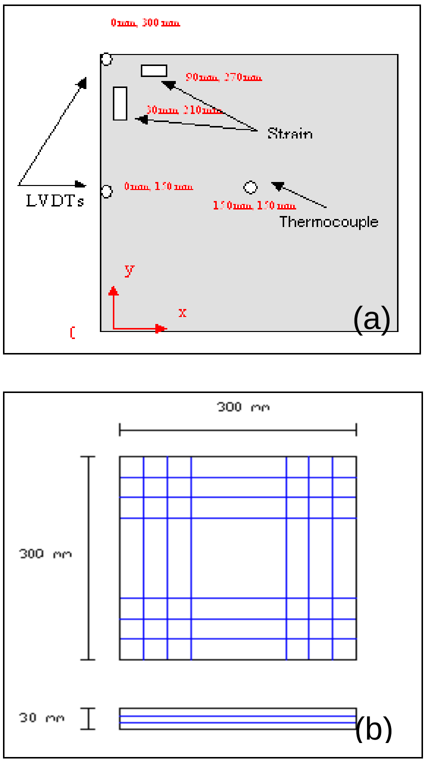


Figure 12. Slab instrumentation (a) and reinforcement lay out (b).

The tensile warping stresses developing in the slab are given by *[Bradbury 1938]*:

$$\sigma_w = \frac{(c)(E)(e)(\Delta T)}{2} \qquad (2)$$

where: σ_W= slab edge warping stress; C= Coef't, a function of slab length and radius of relative stiffness; *E*= Modulus of Elasticity of PCC; *e*= Thermal coefficient of PCC (0.000005/^{0}F, or 0.000009/^{0}C; *ΔT*= Temperature differential between top and bottom of slab

It is obvious from equation (2) above that one way to minimise warping stresses caused by temperature difference between the top and bottom of the slab is to keep *ΔT* minimum. Therefore, the ultra-thin white-top slab with non conventional reinforcement was adopted. The slabs were supported on quarry sand. An infra-red (IR) lamp was placed above to simulate ambient (sun) temperatures. The temperature at top and bottom surfaces, the deflection and strain at the corners and edges were measured. Specimen preparation and instrumentation is shown in Table 5 and Figure 12 respectively.

Due to time restrains the following *240-minutes long "day*" was proposed:

a) The IR lamp was placed at 400mm above the surface of the slab and was switched on for 45 min. to simulate sunrise.

b) The IR lamp was lowered to 300mm and left on for 30 min (noon).

c) The lamp was lifted up to 400mm and left on for 45 min (sunset)

d) The lamp was turned off for 120 min. (night time).

Table 5. Summary of specimens prepared for testing.

Material	Main Reinforcement	Fibre quantity in mix design	Comments
Polymeric concrete	N/A	N/A	Polymer mod. plain concrete slab used as ref.
Polymeric concrete + BarChip	BarChip wires 12 top + 12 bot	2 kg/m^3	2-layers of Barchip wire
Polymeric concrete + BarChip	BarChip wires 12 top + 12 bot	3 kg/m^3	2-layers of Barchip wire
Polymeric concrete + BarChip	BarChip wires 12 top + 12 bot	4 kg/m^3	2-layers of Barchip wire
Polymeric concrete + BarChip	BarChip wires 12 top + 12 bot	5 kg/m^3	2-layers of Barchip wire

A series of readings were taken during the above time period; a sample of the results is presented below. Figure 13 shows the variation of temperature difference with time between the top-side of the slabs exposed to IR radiation and their bottom-side, for slabs with different amounts of synthetic fibres. It is obvious that the performance of all these slabs is very similar, as the temperature difference increases in the "*morning*" when the IR lamp is 'ON' and decreases in the "*evening*" when it is 'OFF'. The temperature difference changes sign when the temperature at the top becomes less than that at the bottom. Finally equilibrium is reached after a long period (not clear in Figure 13).

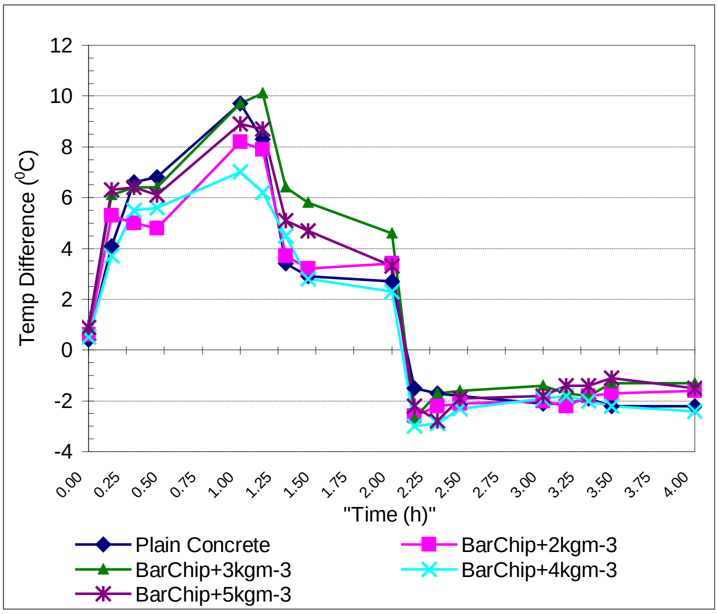


Figure 13. Variation of temperature difference with time for slabs with different reinforcement.

Figures 14 & 15 show the variation of corner and edge displacements during the same time period, demonstrating a trend for the displacement to decrease with increasing amount of reinforcement. However, there seems to be a limit to the rule, rather obvious in Figure 14, where the 5 kgm^{-3} amount of synthetic fibres graph is plotted above the corresponding 4 kgm^{-3}. This is probably due to the fact that the particular slab has been "saturated" with fibres and therefore lost some of its stiffness toughness and strength.

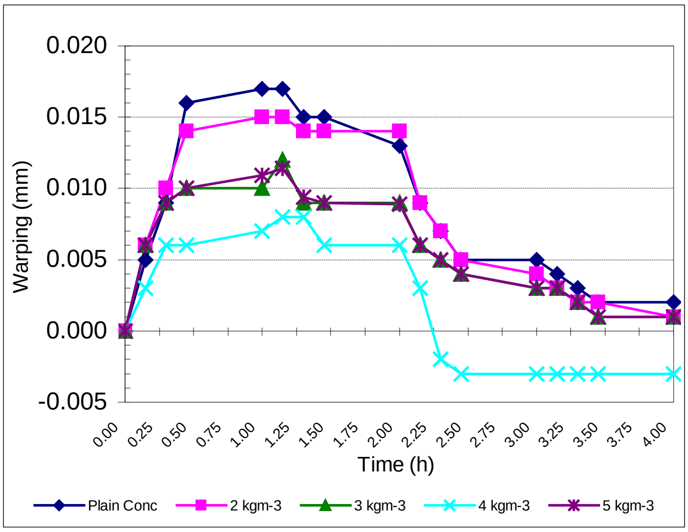


Figure 14. Variation of corner displacement with time for slabs with different amount of synthetic reinforcement.

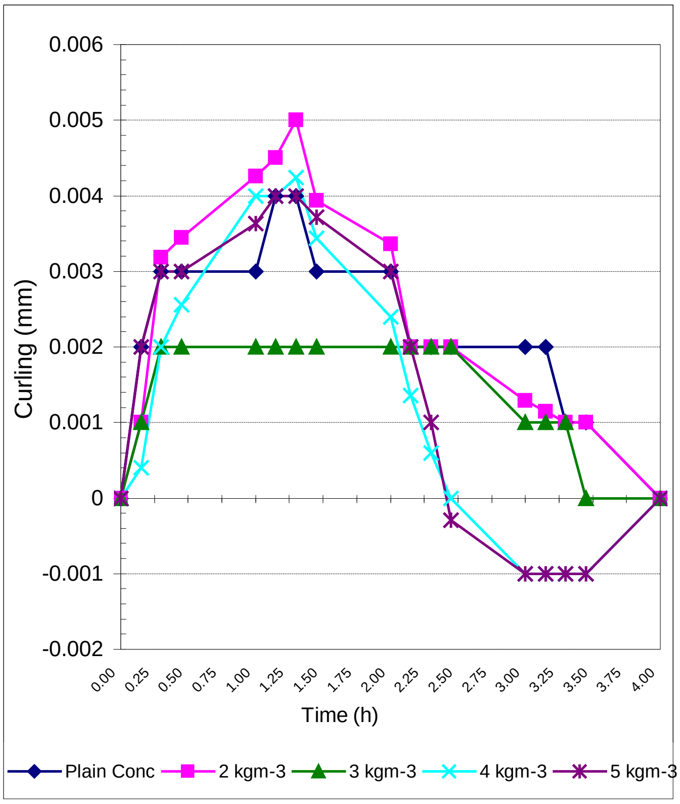


Figure 15. Variation of edge displacement with time for slabs with different amount of synthetic reinforcement.

5. CONCLUSIONS

This paper demonstrates the need for fundamental improvements in the maintenance costs, traffic management, long-term performance and rehabilitation of concrete pavements based on a more sustainable approach. This can be possible by applying environmentally friendly, long-term solutions such as optimising the design, and redrafting the construction and rehabilitation procedures of their repairs. Even greater benefits can be claimed by combining existing design trends, philosophy and know-how with synthetic fibre and bar reinforcement. Specifically:

1. It is possible to go for a wholesale replacement of the traditional steel reinforcement with new, innovative, corrosion free, easier and faster to apply synthetic alternatives such as BarChip which can make a positive contribution to flexural resistance, crack control and bond strength of the rehabilitated pavements.

2. It is possible to achieve a good bond between the old pavement and the overlay by treating the surface of the old pavement. However, there seems to be an optimum *degree of roughness* before bond performance is reduced again.

3. Bonded concrete overlays perform and behave like reinforced concrete with strain distributing linearly across the depth of the beam under tests.

4. Warping at the corners and curling at the edges caused by thermal loads decreases with amount of synthetic fibres and reinforcement. Once again, there seems to be a limit of fibres each concrete specimen can handle after which the later looses stiffness and toughness and fails prematurely.

Finally, it is clear that further research is needed for continuously reinforced bonded concrete overlays to be successfully applicable. This research work should be consisting mainly of site data collection but also accurate numerical representation.

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