Discussion: Optimum design of sustainable concrete pavements

B. P. Hughes

J. N. Karadelis, *Coventry University*

This timely paper, seeking to demonstrate the way for a more rigorous analysis and design of continuously reinforced concrete pavements (CRCP) and bonded concrete overlays (BCO), is welcome. Tension stiffening is important and it is also dependent on the bond between reinforcement and concrete. However, it is not necessarily sensitive to changes in bond strength resulting from different types of reinforcement.^{14,15} Thus, combinations of fibre and rebars (section 3.2) may not provide the expected thermal crack widths and reduced values for maximum crack spacing, as a bar with half the bond strength will have about twice the crack spacing, resulting in larger crack widths. Furthermore, axial tests carried out by Fields and Bischoff for steel and glass fibre reinforced polymer concrete have shown that the reinforcing ratio does not influence tension stiffening.¹⁶

Section 5, on BCOs, may indeed be a winner if designed and constructed successfully, though there are currently certain barriers in need of removal. First, an excellent bond between overlay and worn pavement has to be achieved. Second, the BCO has to provide good shear resistance across an old crack (although it is understood that this does not constitute a serious problem). Third, it is the reflection cracking which, in the author's opinion, is unavoidable and has to be controlled and retained within the BCO. Also, local flexural stiffness at sagging positions has to remain high if existing cracks or other discontinuities are to be controlled. Finally, delamination at the ends or the sides of the pavement is a further problem requiring detailed consideration.

Preliminary tests carried out at Coventry point towards the possibility of accomplishing good bond strength between the old pavement and the all-new polymer-modified concrete (PMC) overlay. These tests were based on simple prismatic specimens joining together OPC and PMC at a shear plane of 45° and undergoing direct compression. In addition, specimens undergoing flexural tests and developing a horizontal shear plane at the interface between the two concretes were tested. All of these performed relatively well but have shown that although initially the strength increases with surface roughness, there is a limit after which a loss in strength is detected. Shear resistance increases with the thickness of the overlay but if an economic solution is sought the volume of the polymeric concrete used as an overlay has to be kept to minimum.

There appears to be a misprint in the antipenultimate line of the first paragraph in section 5.5. The requirement as given previously by the author (author's reference 11) was that M_{U1} should not be less than $2M_R$. It is assumed that is what should have been stated here, since M_{U2} will be much smaller than M_{U1} .

Thermal stresses are liable to cause curling and warping at the edges and corners of the BCO, resulting in delamination. Conventional transverse and longitudinal reinforcement greatly restrains curling and warping but it is expensive and time consuming to be placed in long stretches of roads. This construction method cannot beat black-top. Vertical restraints in the form of beams cause the same drawbacks. At Coventry, we have been experimenting with a synthetic (modified polyolefin) reinforcing fibre, which has a contoured surface similar to steel to maximise bond and a high tensile strength (550 MPa). We are aiming for a wholesale replacement of steel reinforcement by providing a 'cocktail' of synthetic fibres as secondary and mesh as main reinforcement.

Author's reply

I accept that combinations of fibre and rebar may not perform as expected and that within a limited range of reinforcing ratios tension stiffening can be related to the reinforcing bar stiffness but is independent of both concrete strength and reinforcing ratio.¹⁵ The lower the reinforcing bar stiffness the longer are the pull-out and debonded lengths (due to the Poisson's ratio effect) and the wider the crack spacing and crack widths. Thus although the tension stiffening for the reinforcement lengths that remain bonded between cracks may be greater, the crack widths and extensions for the debonded lengths are also greater. These two effects may cancel out when considering the overall deflection for a suspended beam or slab. However for a pavement on grade it is the major losses in stiffness at the cracked sections that are important, not the slight increases in stiffness along the long lengths of already very stiff uncracked pavement. The uncertainties for fibre/rebar combinations are therefore essentially those affecting crack width formation and development rather than tension stiffening of the reinforcement between the cracks.

Again I accept that successful BCOs have not been achieved very often in the past. Careful attention to all the necessary requirements (especially the new critical criteria—the semi-rigid model and the

dual cantilever concept) should ensure successful BCOs not only in temperate climates but also under more variable (including freezing and thawing) climatic conditions. PMC with fairly low polymer content should facilitate improved bond to most well-prepared concrete surfaces at only a slight premium in cost so I would expect good results for the tests at Coventry. There is indeed a misprint in section 5.5. It should read: $M_{U1} \geq 2M_R$.

Extensive experimental evidence, including full-scale site trials will be necessary to enable effective average bond strengths to be obtained for comparison with the corresponding values obtainable with conventional steel mesh or rebar. Nevertheless, with this approach, a construction method for sustainable roads and road base clearly becomes possible which could rival that for black top. Two problems would still remain. For minor roads the edges would need to be incorporated into continuous kerbs to provide the necessary edge restraint against curling. For major roads with a hard shoulder strips of steel reinforcement mesh would unfortunately still be required along the free edges to reduce curling and warping. Handling relatively narrow strips of steel mesh for the edges only is of course easier than handling large sheets for the entire pavement. Corrosion of the synthetic reinforcement is not a problem so a more convenient alternative to the conventional end restraint with cross-beams is suggested below.

The continuous synthetic reinforcement at either end could be deflected down from mid-depth to about two-thirds depth and additional steel reinforcement mesh placed on top so as to be just below mid-depth with any transverse steel bars lying below the main longitudinal steel bars. The upper concrete layer can then be placed and compacted in the normal way. Five transverse saw cuts can then be made down to just above mid-depth ensuring that the steel reinforcement is not cut and that no transverse steel bars lie along or immediately adjacent within 50 mm of the bottom of the cut (i.e. adequate steel cover is still provided). Four transverse saw cuts can be made at s_{min} spacing from the end of the pavement and the remaining saw cut spacing increased to s_{max} . Site trials will indicate if more or fewer saw cuts can be used and if they are suitably spaced to act as slowing down bumps as vehicles come to the end of the continuous concrete road or motorway, and close enough to avoid noticeable curling either side of each cut. The end lengths should be carefully pre-cracked at the cuts at a young age (say seven days) using a suitable heavy vehicle (or vehicles in line abreast) and the cuts suitably sealed. The normal yellow slowing-down lines can then be run along each of the cuts to standardise the bumps and protect the edges to each cut.

S. Alexander, WSP Group, UK

The author does not put numbers into equation 2 for ρ_{crit} , but in Ref. 7 0.35% is derived for grade 28/35 concrete using $g_s = 1.1$. I have derived significantly higher values, mainly by allowing $\pm 30\%$ scatter to f_{ct} but also allowing for the concrete strength to be above the minimum specified.¹⁷

The role of creep in relieving early-age contraction stresses (section 3.2.4) could be worth examining in more detail. In Ref. 17 figure 5 shows the critical points for cracking being at 5–10 days and then at 2–5 years (or even later), the reason for the gap being the alleviation of the early-age contractions by creep.

Ref. 14 also derives a long-term reinforcement requirement of around 1.8 ρ_{crit} (3.2.6), but the paper seems to say that 1.25 ρ_{crit} can be enough (3.2.7).

The difference between seasonal and daily temperature effects is important, as the tensile strength of concrete is lower for the former than the latter (ratio understood to be approximately 0.7).

I concur with the author's disappointment in not being able to quantify the minimum amount of fibres because of not knowing K . The critical volume fraction n_{crit} is presumably quite high, possibly over 2% while about 0.5% (approx 40 kg/m³) is as much as can usually be put into a mix.

Finally, was I alone in not realising that Fig. 2 is a plan while Figs 1 and 3 are sections?

Author's reply

I agree that at first it may appear that ρ_{crit} should be higher and be related to the mean cube strength if yielding of the reinforcement is to be avoided. However although the reinforcement must be able to crack the concrete it is clear on reflection that for a member with side restraint and end restraint it is the weakest concrete elements that will crack first (i.e. weakest link theory). Hence just as the characteristic strength can be considered for the reinforcement, it can also apply for the tensile strength of the concrete when it undergoes its first major restrained contraction, that is, at early age. The characteristic direct tensile strength of the concrete at early age can be taken as $0.12 f_{cu}^{0.7}$ and the partial factor of 1.1 is applied to reduce the probability of reinforcement failure yielding to less than 1 in 20 for the first crack.¹⁸ BS 8007 therefore uses the expression $1.1 \times 0.12 f_{cu}^{0.7}$ to obtain the value of 1.6 MPa for f_{ct} for grade 35A concrete at early age (e.g. 3 days) where f_{cu} is the characteristic cube strength at 28 days.

As pointed out, a major unknown is the actual maturity of the concrete when it cracks. The cracking mechanism assumed in BS 8007 is a true maximum (or multiple) cracking mechanism that is strain controlled. Once cooling starts from the peak hydration temperature the concrete contracts towards a number of fixed centres along the base of the member. Interspersed between each fixed centre is a potential crack position where maximum straining occurs at the 'weakest link' between the two adjacent fixed centres. If the strain controlled member is also fixed at the ends then the construction joint, for example, is most likely to be a 'weakest link' and potential crack position. The BS 8007 (Hughes-type) equations assume that the relative slip between steel and concrete at the crack can be calculated by considering only the movement of the concrete within the bond slip length s_{min} and ignoring that of the reinforcement.¹⁶ In other words, outside the bond slip length s_{min} the base is assumed to be fixed without any sliding or shear lag such that the reinforcement strain and stress is zero.

Note that for strain compatibility any tensile strain that occurs in the reinforcement at the crack and along the 'slip zone' between concrete and reinforcement must be compensated by compression strain in the reinforcement adjacent to the non-slip bonded lengths at the fixed centres. Thus the simplifying assumptions made in BS 8007 ensure that a compressive force assists the tensile force at the crack to provide more than an adequate safety factor against yielding which in any case is already increased by a partial safety factor of 1.1. This compressive force acting as an additional safety factor has always been acknowledged.^{8,18} The direct and simple approach as used in BS 8007 is considered better than introducing

unnecessary complications such as an estimated mean strength at some later age. Once initiated the cracks can readily propagate through adjacent areas and across the entire cross-section. Thus an effective and economical ρ_{crit} is best related to the characteristic direct tensile strength at first major straining due to the early thermal contraction irrespective of whether or not cracks are actually detected then or later. Higher steel ratios may well be necessary for other reasons as indicated in the paper (e.g. no end restraints and low sliding friction at fixed centres) but this will not be because the ρ_{crit} value needs to be increased *per se*.

I agree the role of creep is worth looking at in more detail. Examining the role of creep as shown in Fig. 5 of Ref. 17 can explain why the simple assumptions that were necessarily made in the early work on which BS 8007 was based could give surprisingly good agreement with maximum crack widths measured on site. The major roles played by bond creep between concrete and reinforcement in the vicinity of a crack, creep in the immature concrete drastically reducing the effect of the early thermal movement expected from the temperature readings and finally further creep in the mature concrete reducing the effect of the long-term shrinkage were readily apparent from the earliest site data. The creep due to the resultant early age effects (primarily thermal but also including early autogenous shrinkage) appeared to be given by a global reduction factor of about 0.5. Similarly, and perhaps surprisingly, the long-term thermal and shrinkage effects also appeared to be given by a global reduction factor of 0.5. The latter was assumed to be because the creep took place over a far longer period of time while the rate of creep with time progressively reduced.

Extensive site evidence obtained subsequently has shown that the early simplifications and approximations have continued to provide good predictions for a wide range of structural members subjected to the maximum cracking mechanism. The only members that have been found not to agree with the predicted crack widths (and were in fact much wider) were those not subjected to continuous side restraint and not considered in BS 8007, that is suspended beams and slabs and continuous pavements on a polythene sliding layer and similar members subjected to the minimum cracking mechanism.^{7,19,20} These members crack suddenly with shock as the stored strain energy is released—there is little or no side restraint to dampen the energy release as there is for the BS 8007 type mechanism. Sliding layers under CRCP should therefore be avoided since much more reinforcement is required to control crack widths adequately.

The value required to introduce an additional direct tension crack across the mature concrete section in a fixed-end situation appears to be generally agreed at around $1.8\rho_{\text{crit}}$. Just as $1.1\rho_{\text{crit}}$ can be taken as the minimum reinforcement requirement for the immature concrete, $1.25\rho_{\text{crit}}$ can be taken (from the 'thermal shunt concept') as the minimum in the mature concrete for long lengths of pavement between expansion joints subjected to daily thermal cycles and movements.⁷ If the ends are not fixed the daily thermal changes can shunt each pavement segment backwards and forwards between the cracks to achieve equilibrium positions as the forces transmitted across the cracks alternate between compression and tension. The resultant force required to slide the segment horizontally is only a fraction of the force required to crack the mature concrete section: hence the shunt theory value of $1.25\rho_{\text{crit}}$. However, as pointed out in the paper, other considerations may be more critical, such as a

higher steel ratio to satisfy w_{max} (section 3.2.5), the required flexural resistance (section 3.3) or the fatigue life (section 3.4.3). Thus if fibres are not used then values of $1.4\rho_{\text{crit}}$ or $1.5\rho_{\text{crit}}$ minimum reinforcement across cracks for semi-rigid design may well be required anyway to achieve the required fatigue life.

I agree with the discussor that there are major differences between seasonal and daily temperature effects. Shunt theory applies, for example, purely because of the very significant frequent reversals due to daily thermal effects.

Combining fibres with rebar is undoubtedly the way forward in my view for sustainable pavements in particular. Hence the presentation of some basic theory and urgent plea for research and site trials to determine suitable K values for the best fibres currently available. The critical volume fraction n_{crit} is quite high and far higher than can be used in any normal concrete mix. While the inclusion of low volume fractions of fibre on their own may produce some minor benefits in the mature concrete, these are small compared with the major improvements possible with a critical volume fraction n_{crit} . As indicated in the paper the most practical, economical and efficient solution for concrete pavements is to achieve about $0.5\rho_{\text{crit}}$ with fibre (i.e. about $0.25 n_{\text{crit}}$ for mature concrete) and make up the remainder in rebar. The volume fractions quoted by Mr Alexander for normal concrete are of the right order. The very common misunderstanding that fibres alone without any rebar can achieve a critical volume fraction and hence multiple cracking in direct tension probably arises from test results on *small laboratory specimens* for an *oversanded* and *small maximum aggregate size* concrete containing as much fibre as possible *tested in flexure* and not in direct tension (e.g. see Ref. 21).

Finally: possibly not! Fig. 2 in the paper should have indicated that it was a plan view.

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