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Pothole formation: experiments and theory

This article most definitely does not represent the last word in pothole research. Rather it is a snapshot, intended to give some insight into the issues that are being or need to be investigated. The background of course is the seemingly endless need for resources for pothole filling just to keep the highway network in some sort of order, a need that is seen not only on the local road network but also on many of our motorways and trunk roads. And all of this begs the questions: Why? And what can be done about it?

The truth is that roads have always broken up. For many decades, so-called analytical pavement design – the approach that underpins the Highways Agency's design standards – has involved calculating the tension that forms in the asphalt under each HGV wheel load and relating that to the number of load applications likely to cause failure. So it is accepted that asphalt does not last for ever. It is also accepted that tension occurs both on the surface and at the base of the asphalt and that cracking can originate on the surface. This can be simulated theoretically and it allows decisions on the required overall thickness of a pavement to be taken with reasonable confidence.

But there is a large difference between a top-down crack and a pothole. Cracked roads can be driven over for years without any discernible problems for the motorist; potholes on the other hand are a considerable nuisance resulting in loss of service and, sometimes, actual vehicle damage.

What is a pothole?

For a pothole to form there must be loss of material from the road, and this is material that had previously been attached through bituminous bonds. The fundamental problem therefore is the premature breaking of bituminous bonds, either liberating numerous individual stones resulting in a fretting-type pothole or allowing whole 'flakes' of surface course material to become detached (**Figure 1**). And this reduces the question to: Why do these bonds break?

Figure 1

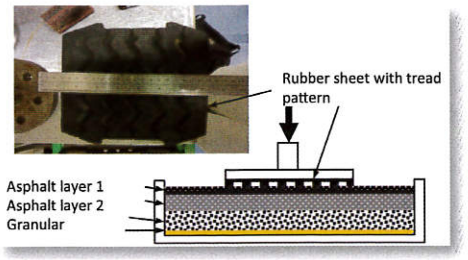

Figure 2

Figures 2 and **3** show a simple laboratory test on a two-layer slab of asphalt overlying a crushed rock foundation and some of the data obtained (Rahman and Thom, 2012). The load was simply vertical rather than through a rolling wheel (to allow increased magnitude and numbers of loads) but it was applied through a ribbed rubber pad that reasonably realistically simulated a tyre contact. And this test at least managed to imply what every highway engineer knows, that pavement surface damage forms much more readily in the presence of water, although the freeze-thaw result on the right side of the figure should probably be discounted as temperatures were not well controlled. While this type of loading is unable to create an actual pothole, it is reasonable to suggest that the breaking up of pavement materials that occurred (measured as a total length of cracking and an enhanced permeability) represents the necessary prelude to potholes on the road.

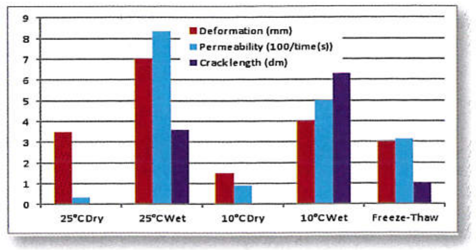

Figure 3

How strong is asphalt?

Asphalt is an interesting material. If it is properly designed and constructed it will have a good, interlocking skeleton of stones within it giving stability and resistance to rutting, although it also relies on the bitumen to 'glue' individual stones together. In fact this 'glue' is more than bitumen; it is a mastic comprising bitumen and filler particles, basically rock dust of approximate size 5-100 microns, and it is the strength of the mastic that determines how much tension an asphalt can carry. **Figure 4** shows data from a series of direct tension tests (Thom et al, 2006) carried out on different mastics at various temperatures and loading rates and this suggests that a mastic with a reasonable filler content might have a strength of nearly 10MPa under most operating conditions.

On the other hand, this reduces at the left hand side of the figure, representing test conditions of either low temperature or rapid loading rate or both. Whatever the actual strength, therefore, it appears that it will be reduced in the winter and/or when hit violently by some impact type load. Under these conditions, its behaviour will be rather brittle, shown by the fact that the strain at failure is small on the left side of the figure and the energy required to cause fracture is therefore also relatively small.

The conclusion therefore, unsurprising to all highway engineers, is that asphalt is weaker, more fragile and in more danger of cracking in the winter than in the summer. Incidentally, the reduced failure strength on the right side of **Figure 4**, representing warm conditions or slow loading, is not a real cracking problem because it is combined with high failure strain and therefore high 'toughness'.

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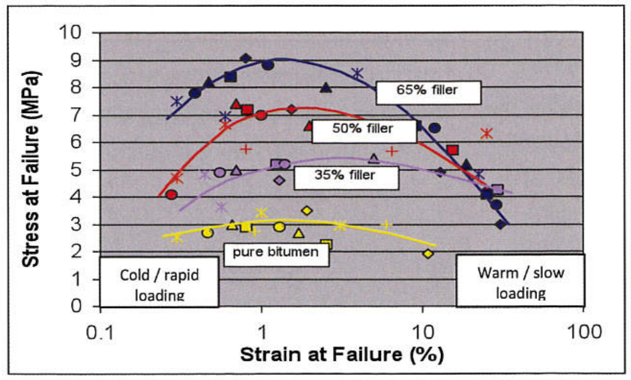


Figure 4

Why does water increase damage?

At this point it should be noted that this study will not consider the undoubted damaging effects of freeze-thaw in breaking bituminous bonds, but only the influence of water. With respect to water, there are really only two possible damage mechanisms:

1. the water might in some way attack the bituminous mastic that binds the stones within an asphalt together;
2. the water might lead to increased tension in the asphalt for some reason.

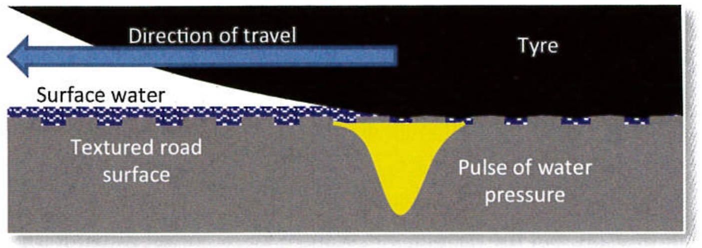


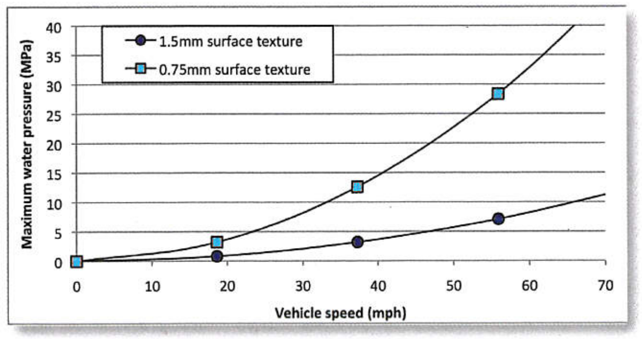
Figure 5

The first of these is known to have some validity. It is common to evaluate asphalt durability by testing its strength or stiffness before and after soaking in water for a specified period, and it is standard practice to accept a material so long as the soaked strength or stiffness is at least 80% of the dry value. The problem is that stones generally prefer water to bitumen (hence the need to dry out thoroughly as part of hot-mix asphalt production) and minute traces of water can work their way between the bitumen and the stones or perhaps through the stones themselves if they are sufficiently porous.

Nevertheless, it is the contention here that the second reason is the more critical with respect to pothole formation. And to investigate the issue further it is necessary to work out the pressure that might be generated within a film of water on a road as a truck passes over. **Figure 5** illustrates the situation in the case where surface water is sufficient to fill the voids between the tyre and the road surface. The load on the tyre causes each element around the exterior to compress, reducing tread depth; more importantly, individual stones on the surface of the asphalt will indent into the rubber, further reducing the volume available to hold water. Since water is effectively incompressible, the volume can only reduce if surplus water is expelled from the front and sides of the tyre; and if water escapes, that means it must have been 'accelerated' to some velocity horizontally; and Newton's 2nd Law states that a force would be required to induce that acceleration, a force that then implies a pulse of pressure in the water as it is 'squeezed' out.

This pressure is not impossible to compute – at least approximately. It is necessary to idealise the tread pattern and the texture of the road surface, and also to assume a value for the modulus of tyre rubber (10MPa assumed here although lower values are possible); and the result is that a pressure pulse is predicted at the leading edge of the tyre contact zone, as illustrated in **Figure 5**, a pressure pulse that can achieve very large magnitudes, albeit over a very short time scale. **Figure 6** illustrates typical predictions, indicating the importance of road surface texture. It is immediately clear that, if these computations are of the right order of magnitude, then the pressure in the water will commonly be much greater than the tensile strength of the asphalt, a potentially dangerous situation.

Figure 6



Why is water pressure a problem?

In a nicely closed asphalt surface, this pressure would be no problem at all. It would simply be a pressure acting downwards onto the surface, and asphalt has little problem withstanding compression of this sort. But the danger with water pressure is that it acts in all directions, wherever the water can penetrate, and if the water already fills a crack, or even a modest depression within the surface, then it will act laterally onto the asphalt face. This is more difficult to resist than a purely vertical pressure. Worse, in a moderately voided asphalt the water can penetrate the voids and then, when under pressure, it will try to 'explode' the asphalt apart, leading to an attrition or fretting type pothole.

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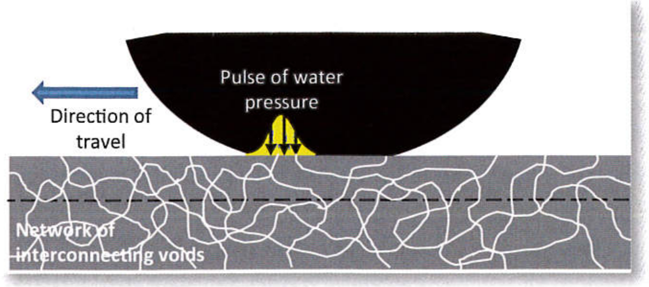

Figure 7

Consider the asphalt as a slightly porous material with a series of interconnecting voids within it, illustrated in **Figure 7**. If there are connected paths in which the water can flow, then this has two consequences. A positive consequence is that pressure will dissipate as it flows into and through the connected voids; a negative consequence is that these connected voids give the water access to potentially damaging areas. Again, simplified analysis is possible, treating flow through the voids in a similar fashion to pipe flow. This allows a reduced pressure to be estimated, and this can be linked (admittedly rather approximately) to critical void size and so to permeability, which in turn can be linked experimentally to void content. There are certainly many assumptions to be made, but the result is that it is possible to estimate the pressure within a network of interconnecting voids inside the asphalt surface course. This pressure acts on the asphalt surrounding each void and so causes a tensile stress within the material. **Figure 8** shows the results of such computations, as an approximate function of surface course void content.

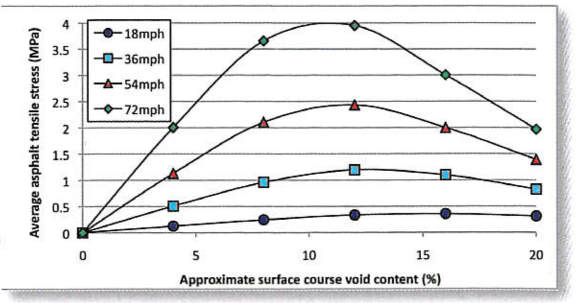

Figure 8

Figure 8 is interesting in that it suggests that a surface course should either be dense, with low void content and so of very low permeability, such as a traditional Hot Rolled Asphalt or a properly designed Stone Mastic Asphalt, or it should be of high void content and permeable, such as a Porous Asphalt. Materials at an intermediate void content, which almost certainly include many of those currently permitted on Highways Agency roads, give rise to the highest tensile stresses due to water pressure and so are most susceptible to breaking apart even without any obvious cracking having developed. It should also be noted that the stresses shown in **Figure 8** are averages and that local stresses will be much higher, quite conceivably higher than the tensile strength of the material. And even if the stresses are lower than the nominal tensile strength of the asphalt, the effect of repeated water pressure events can still be to cause breakage due to fatigue.

A very clear message follows from **Figure 8**, again a message that will surprise few highway engineers, and that is that we need to be very careful as to which materials we accept for surface course application if we wish to avoid fretting-type potholes. We also need to specify and control the production of such materials appropriately.

Are surface cracks a problem?

To investigate the effect of cracking, the case of a vertical crack in the asphalt surface, filled with water, has been explored. The water within the crack, when pressurized, forces the asphalt to distort, increasing the space available for the water and so reducing the pressure. **Figure 9** presents calculations assuming stiff asphalt (appropriate to winter), a low surface texture depth (0.75mm) and a good tyre tread (8mm), although it is found that neither texture depth nor tread have as much impact within the crack as they do at the surface. Asphalt stiffness on the other hand is an important parameter here, with winter pressures predicted to be much higher than those in the summer, providing a further reason why pavement disintegration is so much more prevalent in the winter.

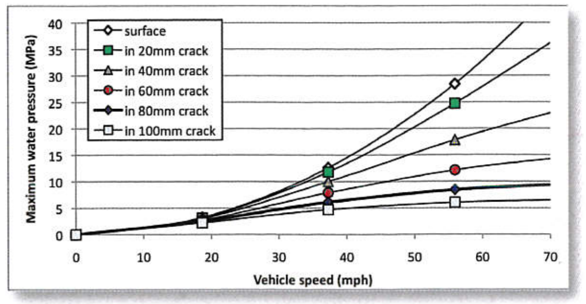

Figure 9

Figure 9 suggests that there are likely to be pressures acting on the faces of cracks that exceed the tensile strength of the asphalt, at least in shallow cracks. However, at the time that this pressure acts there will generally also be a large vertical pressure acting on the road surface, and this will tend to prevent any fragments of material from breaking off; thus it would appear that a vertical crack on its own presents little danger. But this is not the case if water can penetrate not only down into a crack but also laterally, for example at a debonded interface. **Figure 10** illustrates this case. Again, calculation can only be indicative.

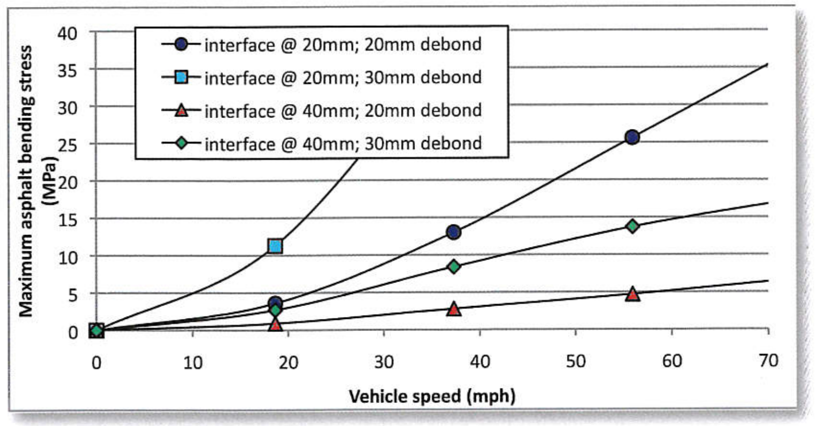

Figure 11

Nevertheless, **Figure 11** shows an approximate evaluation of the maximum tensile stress induced in the asphalt as pressure from beneath attempts to break off the overlying material. Now admittedly this pressure only lasts for a small fraction of a second, which means that the energy available during each wheel pass is limited, but over the course of many wheel load applications it is clear that the potential exists to fracture the material, assuming that the tensile strength of the asphalt is not significantly greater than 10MPa. The result would be the familiar scenario of flakes of surface course material becoming detached and leaving a pothole.

Two clear points emerge from these calculations. The first is that a crack-resistant material will never give surface water the opportunity to penetrate into regions where it can exert these damaging pressures. The second is that a thin surface course is much more vulnerable to damage from water pressure at a voided or debonded interface than a thicker asphalt layer; the difference between the tensile stresses predicted in 40mm and 20mm thick asphalt layers shown in **Figure 11** is very significant.

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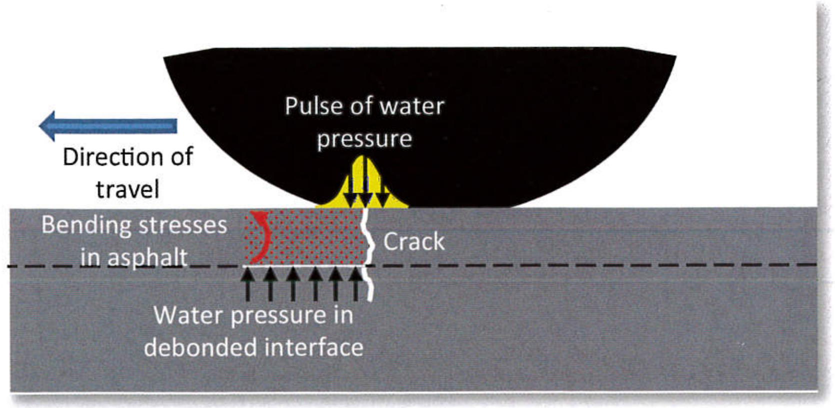

Figure 10

Conclusion

This article has been full of theory – but the problem of potholes is far from theoretical. The principal conclusions from this study would appear to match those that most highway engineers would intuitively make, namely:

1. The type of surface material really matters; it should either be dense and of low permeability or open textured with large voids.
2. Surface course thickness is also important. A 20mm layer is much more vulnerable than a 40mm layer and inter-layer bonding correspondingly much more critical.
3. Surface cracking is not a problem on its own, but becomes a problem where it gives water access to voided inter-layer regions.

References

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Thom N H, Osman S A, Collop A C and Airey G D, Fracture and fatigue of binder and binder/filler mortar, Proceedings of the 10th International ISAP Conference on Asphalt Pavements, Quebec City, Canada, Vol 1, 798-807.