Predicting the effect of rainfall on asphalt surfacing materials

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ABSTRACT: This paper reports an investigation into predicting the effect of rainfall on the properties of four types of asphalt surfacing materials. A rainfall simulator was designed to wet a large asphalt slabs under different rainfall intensities and cross falls allowing water flow across and within the slab to be quantified. The effect of water film thickness on skid resistance was assessed. Test specimens were prepared using gyratory compaction and assessed for water retention and drying out experiments. This showed the importance of understanding how water movement and storage within the surface layer in relation to potential moisture related problems. The effect of increasing number of simulated rainfall events was used to assess the durability of unaged and aged asphalt. The results show that it is possible to determine key performance data without the need for large scale road trials.

1 INTRODUCTION

Asphalt surface courses that are expected to perform better and last longer must consider all of the factors involved in its ultimate performance. It is commonly accepted that damage is caused mainly by traffic load, unsuitable material and the environment. The effects of the first two factors can be estimated for design purposes by empirical and mechanistic methods. However, the effect of simple environmental factors such as rainfall on performance is not as well understood.

Water on the road surface must be drained as soon as possible because it may contribute to accidents and reduce the service life of the material. For example, Rule 227 of the UK Highway Code states that stopping distances will be at least double those required for stopping on dry road (Highway Code, 2008). Water also affects performance by causing bitumen to strip from the aggregate leading to raveling, separation of layers and pothole formation.

Climate change is affecting many countries around the world and is seen as a threat to our common future. In the UK the winters appear to becoming wetter and summers drier with extreme precipitation more frequent. Transport Scotland (2008) have stated that as weather conditions such as temperature, snow, wind, frost, ice and rainfall affect its trunk road network, it's important that they prepare for any climate changes that may alter their weather.

This change in climate whereby the frequency and amount of rainfall is increasing due to global climate changes has important implications on the road user and on the life of the pavement. This formed the basis for the research project summarized in this paper.

2 METHODOLOGY

The basic aim of the research project was to investigate the effect of rainfall on properties such as cross fall, skid resistance and mix durability. A three stage research methodology was developed. Stage 1 considered the design and manufacture of a simple rainfall simulator, known as the Ulster Rainfall Simulator (URS) to assess rainfall-runoff relationships for a range of surface course materials used in the UK. Stage 2 considered the effect of water on laboratory and in-service skid resistance. This paper considers only the laboratory investigation. Stage 3 developed a methodology to better understand the effect of simulated rainfall on surface mix durability. Each stage involved the modification of existing standard equipment or development of new equipment and test methods (Nursetiawan, 2009).

Four types of asphalt surface course material were assessed. Each material was sampled at a UK mixing plant and delivered in 25kg bags. The four materials were proprietary 6mm Open Texture (6mm OT), 10mm Dense Bituminous Macadam (10mm DBM) wearing course to BS 4987-1:2005, proprietary 10mm Marshall Asphalt (10mm MA) and proprietary 14mm Marshall Asphalt (14mm MA). These materials were used to prepare test specimen slabs 1420 x 600 x 50mm in size compacted using a pedestrian single drum vibrating roller. A gyratory compactor was used to prepare 100mm and 150mm diameter test specimens at different void contents using increasing number of gyrations.

Different types of rainfall simulator design were considered. Based on considerations such as cost and space requirements the Simone et al. (2004) design was selected and subsequently modified. Development and subsequent use of the URS involved quantifying the relationships between rainfall intensity, texture depth, cross fall and material void content. Three rainfall intensities (RI) were selected i.e. RI-1 of 31.4mm/h, RI-2 of 54.2mm/h and RI-3 of 78.3mm/h.

3 RAINFALL RUNOFF RELATIONSHIPS

The asphalt surface course variables considered were surface type, texture depth, void content and hydraulic conductivity. The main measurements taken from the URS were runoff and percolation and cross fall. When rainfall of constant intensity falls over a pavement surface, a series of events takes place (Gallaway et al. 1971). A certain amount of water is required at the start to fill surface interstices before runoff occurs. This is referred to as depression storage and is measured in volume per unit area or average depth in mm. It depends on the initial wetness of the surface, degree of surface texture, deformations in the surface and cross fall. Runoff rate then increases to an equilibrium value (Q_{peak}). For an impermeable surface this rate is equal to rainfall intensity. During this period the amount of water retained on the surface increases to its maximum value. The thin sheet of water on the surface at the time of constant runoff, excluding that required for depression storage, is called surface detention. It has the same units as depression storage and can also be expressed as a value at a point or an average over an area. When rainfall ceases, the runoff rate decreases to zero while the depth of water held by surface detention also decreases to zero.

The 10mm DBM and 14mm MA materials were assessed for surface runoff. A wood surface was also assessed to represent an impermeable smooth textured surface. The 10mm MA and 6mm OT were assessed for both surface runoff and percolation. It was found that the time to reach equilibrium condition (t_{eq}) was effected by all of the test conditions i.e. rainfall intensity, cross fall, texture depth and degree of permeability. For example, an increase in rainfall intensity resulted in a decrease in t_{eq}. Figure 1 plots time to reach equilibrium condition (t_{eq}) against cross fall (or slope) for wood, 10mm DBM and 14mm MA at rainfall intensity RI-1. This shows that steeper cross falls result in lower or shorter t_{eq} values. The smoothest surface texture presented by the wood gave the lowest value of t_{eq}, or quickest time to reach equilibrium stage i.e. less flow friction caused by the surface resulting in more rapid runoff.

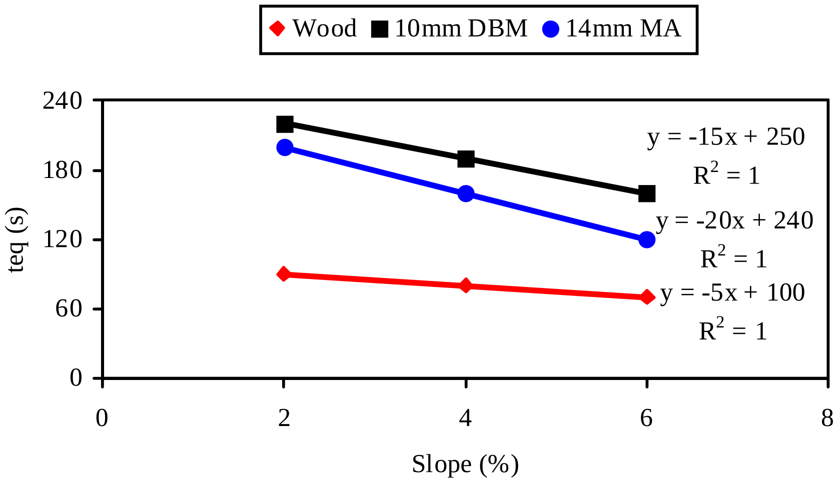

Figure 1. Cross fall vs t_{eq} for rainfall intensity RI-1.

The texture depth (MTD) of an asphalt surface layer has the task of removing the greater part of rainfall under the momentary contact of a moving tire thus maintaining the effectiveness of the finer scale aggregate micro-texture when the road surface is wet. The wood surface was included in the investigation as it had relatively smooth surface textures. Rather than assume a texture depth of zero, a value of 0.081mm was measured for the plywood used. Figure 2 plots t_{eq} against texture depth for different cross falls (slopes) at rainfall intensity RI-1. Increasing the rainfall intensity causes the gradient of these lines to become flatter.

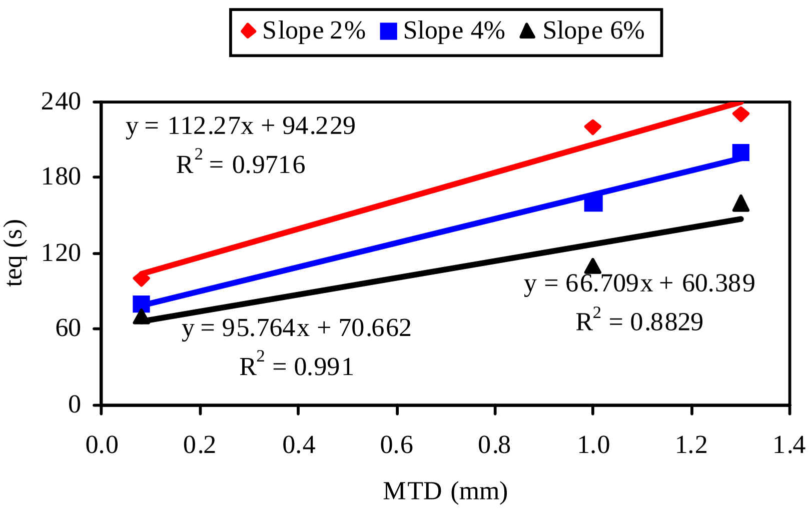

Figure 2. Plot of MTD vs. t_{eq} for RI-1.

The equilibrium stage of a typical hydrograph profile is achieved after the pavement material has become saturated, the amount of water required for depression storage is filled and runoff increases. During this stage, for a typical impermeable surface, the equilibrium value (Q_{peak}) is constant during rainfall duration and equal to rainfall intensity. However for a typical permeable material Q_{peak} will be equal to excess rainfall after total rainfall is deducted by percolation rate. Testing found that higher rainfall intensity produced greater runoff at equilibrium i.e. when the slope of the hydrograph is horizontal. Due to the relatively small size of the URS test rig area it was found that there was little variation in equilibrium values for a given rainfall intensity.

After cessation of rainfall, it was found that cross fall was the most important variable which affects the velocity of water to flow across the surface. In general, it was found that higher cross falls will drain the surface flow quicker and the total volume of water is lower. The measured test period was terminated after 600 seconds for the rainfall-runoff tests. It was evident that water still remained on the surface after this period. This residual water was calculated in terms of water depth and equated to reservoir storage (d_{rs}). It was found that the amount of d_{rs} was influenced by material type and cross fall. Flatter cross falls produced greater d_{rs} values. More permeable materials have lesser d_{rs} values. It is suggested that the d_{rs} values could be used as an indicator of road safety risk in relation to the water exposure time during and immediately after a wet period as it relates to how long a road surface remains wet and so has lower skid resistance.

Four predictive models were developed using the URS test data. The regression analysis found all four models gave significant correlation between the four independent variables. The lowest R^2 was 0.7484 for the d_{rs} model. The models were:

$$t_{eq} = 184.893 - 1.465RI - 11.389S + 40.536MTD + 2.049V_a \quad (1)$$

$$Q_{peak} = 1.898 + 0.282RI + 0.161S + 0.123MTD - 0.171Va \quad (2)$$

$$V_{sd} = 125.645+13.133RI +0.161S +221.854MTD +1.01Va \quad (3)$$

$$d_{rs} = 0.182 +0.0005RI -0.401S - 0.049MTD + 0.0034V_a \quad (4)$$

where t_{eq} = time to equilibrium, Q_{peak} = equilibrium value, V_{sd} = runoff volume, d_{rs} = water depth at depression storage, RI = rainfall intensity, S = cross fall, MTD = mean texture depth and V_a = void content.

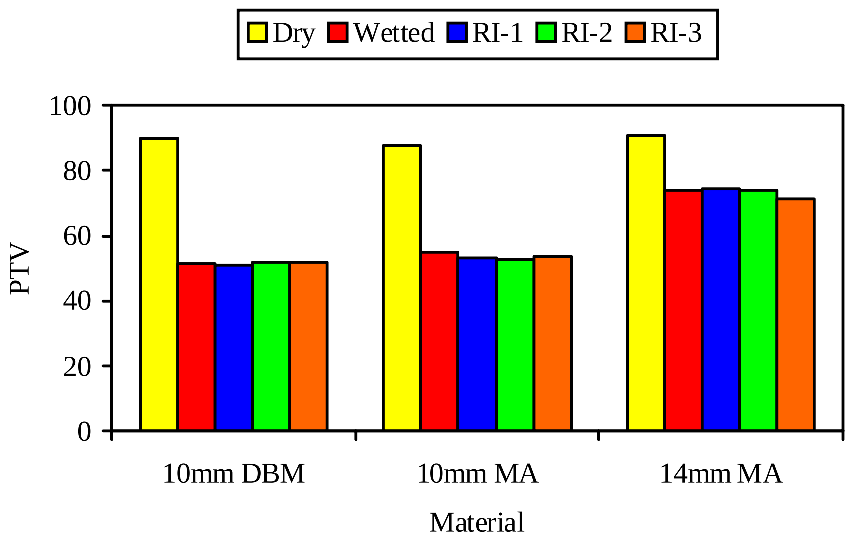

Figure 3. Unpolished skid resistance for the large slabs under different rainfall intensities.

4 EFFECT OF WATER FILM THICKNESS ON SKID RESISTANCE

The effect of water film thickness on skid resistance was assessed in three different experiments and used a pendulum tester in accordance to BS 13036-4:2003. The first experiment assessed the unpolished skid resistance of the large slabs during the three rainfall intensities i.e. RI-1, RI-2 and RI-3 to give three different water depth values on the slab surface. The second experiment assessed the unpolished skid resistance of smaller 305 x 305mm slabs under simulated flooded conditions. The third experiment assessed how skid resistance changed during simulated laboratory trafficking using the Road Test Machine. Figure 3 shows example data for the first experiment and clearly shows that once the slab surface got wet there was little further difference in pendulum test value (PTV) with increasing rainfall intensity or water film thickness within the range used. The large slabs were cut into 305 x 305 square slabs and subjected to flooded test conditions of 5 and 15mm water film thickness (WFT). The dry and wetted data were similar to the results obtained for the large slabs i.e. the pendulum value dropped significantly when the surface was wetted. However, increasing the water film thickness to simulate flooded conditions caused the pendulum swing to be held back giving increased PTV values. This illustrates that there would appear to be a critical water film thickness at which the pendulum equipment cannot be used to measure skid resistance either in the lab or on-site.

In the third experiment the 305 x 305 mm slabs were assessed to determine how their skid-resistance value changed during simulated trafficking conditions using the Road Test Machine (RTM) at University of Ulster. The RTM has a 2.3m diameter table that allows up to ten 305mm square specimens to be subjected to simulated wear using two standard car tires. The RTM is located in a temperature controlled room maintained at 10+/-20C. The table rotates at 10 rotations per minute whilst applying a dead load under each wheel of (5± 0.2) kN (Nicholls, 1997).

The RTM test was stopped at intervals and each slab assessed for change in skid resistance using the pendulum Testing was stopped at 55,000 wheel passes as several of the slab surfaces were suffering from severe raveling. Experiments 1 and 2 had shown that the standard wetted conditions would be appropriate. Figure 4 compares the change in dry and wet polished skid resistance for the 4 asphalt materials. This clearly shows the marked reduction of skid resistance by wetting the surface. This type of testing i.e. subjecting asphalt samples to simulated trafficking and stopping the test at regular intervals clearly shows differing early life changes and how their relative ranking in terms of dry and wet skid resistance develops with time.

The change in texture depth was also measured using the volumetric sand patch test. Figure 5 plots both dry and wet skid resistance according to texture depth. The trend lines found no significant correlation between texture depth and PTV and indicate that skid resistance cannot be predicted solely from texture measurements.

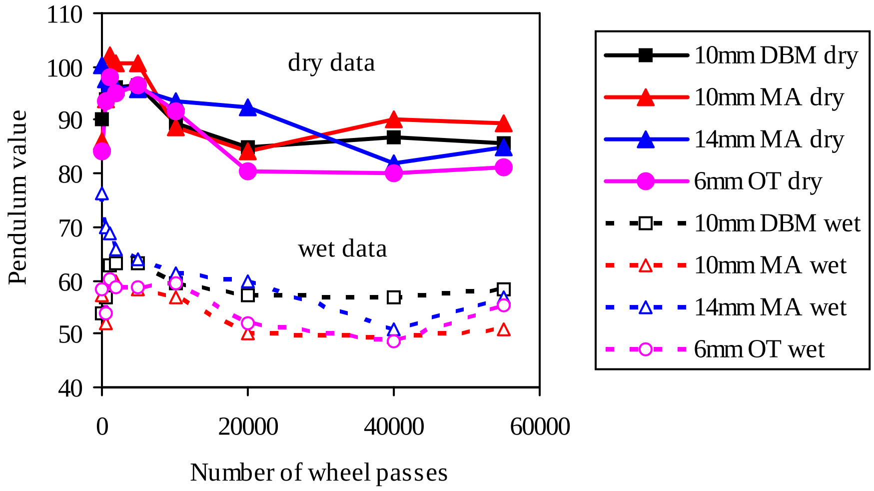

Figure 4. Change in dry and wet skid resistance during RTM testing.

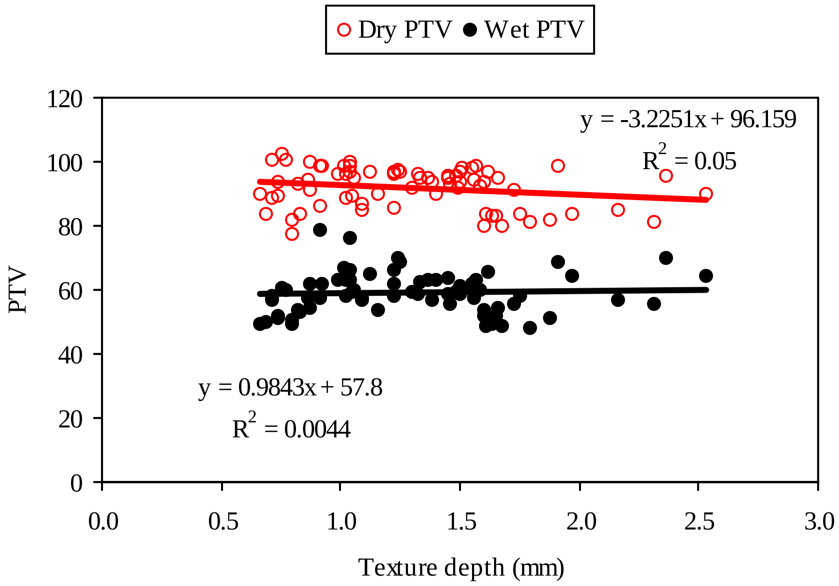

Figure 5. Relationship between dry and wet skid resistance and texture depth.

5 EFFECT OF SIMULATED RAINFALL ON SURFACE COURSE DURABILITY

The third part of the research methodology considered how rainfall is retained on or within asphalt surface mixes and how this may subsequently affect its durability. A series of 100mm diameter test specimens were prepared using gyratory compaction to give a range of void contents. The hydraulic conductivity of each test specimen was assessed using an in-house falling head method developed at the University of Ulster. The time for a 550mm head of water to pass through the test specimen is used as a measure of hydraulic conductivity.

Example hydraulic conductivity data is plotted in Figure 6 to show how permeability relates to void content i.e. the 14mm MA was impermeable with the 10mm DBM being most permeable. The 6mm OT is plotted in Figure 7 and shows good correlation between number of gyrations, air void content and hydraulic conductivity because of its high permeability.

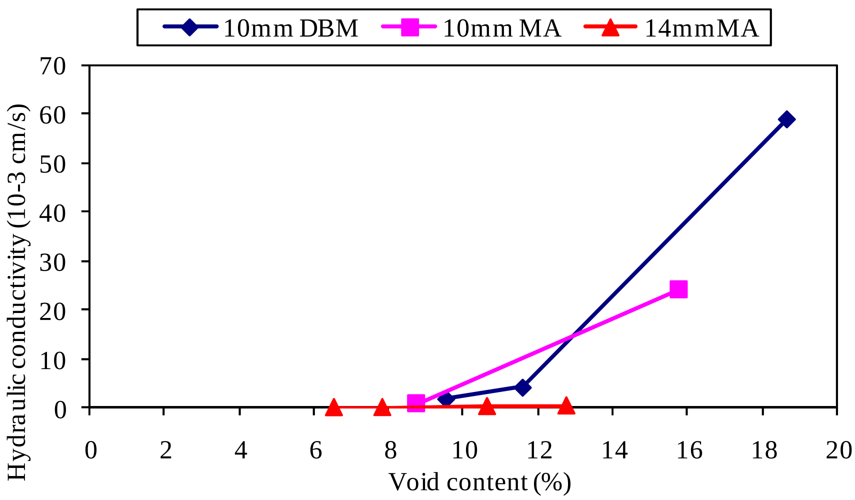

Figure 6. Void content vs. hydraulic conductivity using falling head apparatus for 100mm diameter specimens.

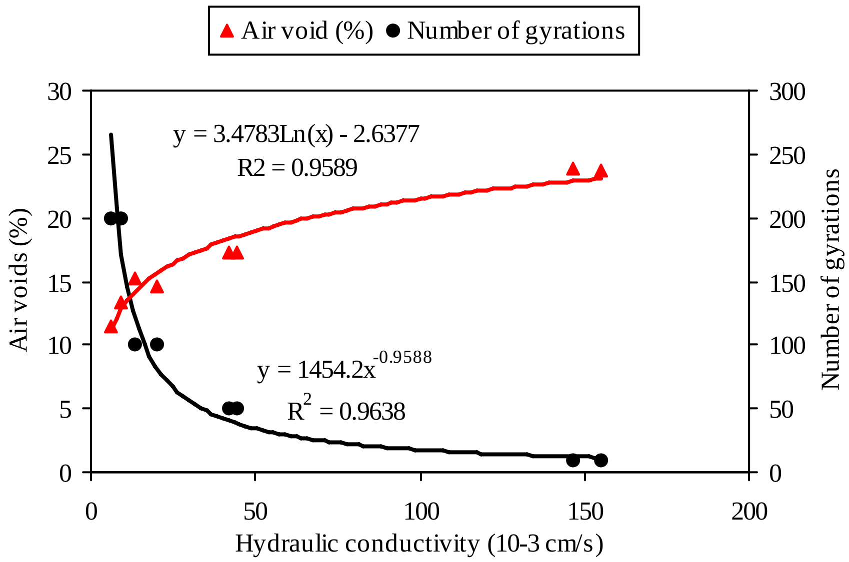

Figure 7. Hydraulic conductivity of 6mm Open Texture specimens.

The base and side of each test specimen was sealed with wax to ensure that any moisture loss would be from the surface. They were subjected to a controlled amount of simulated rainfall and the amount of water retention during a drying out phase determined. Figure 8 plots air void content against the mass of initial absorbed water and shows the 4 surfacing materials to fall into 2 distinct types i.e. those that are impermeable and do not retain water and those that are permeable and retained water with increasing void content. Figure 9 plots the amount of water retained for each of the four materials at their different gyration compaction levels after 20 hours of drying at 200°C. Again there are two distinct groupings present.

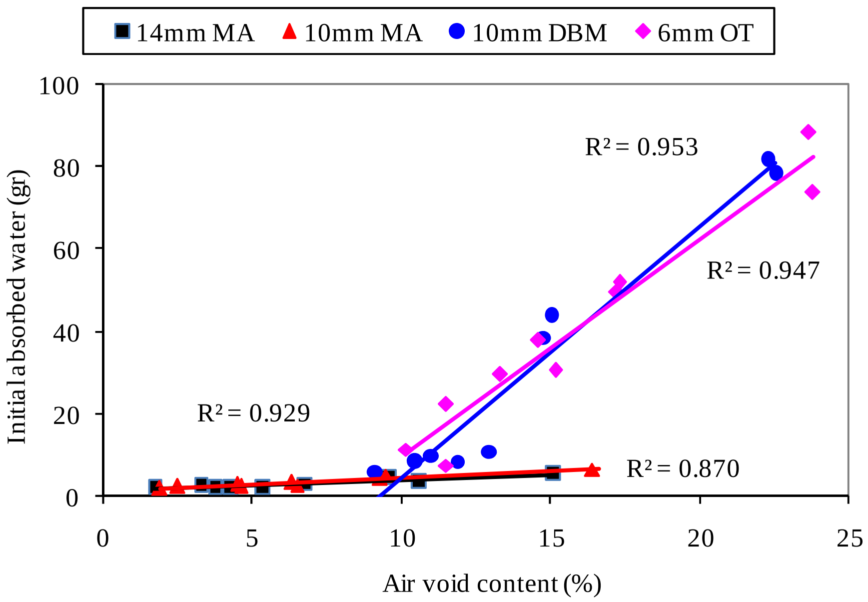

Figure 8. Average mass of initial absorbed water in relation to air void content.

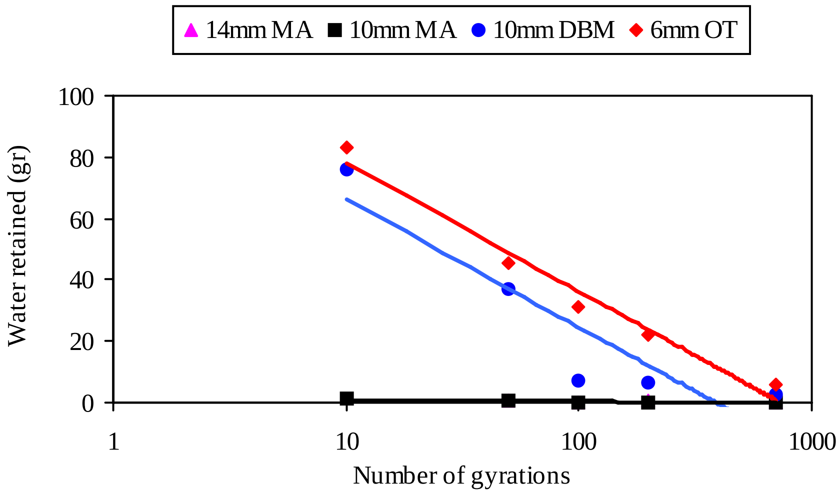

Figure 9. Amount of water retained for different level of compaction after 20 hours at room temperature 20°C.

The investigation then considered the effect of simulated rainfall cycles on asphalt mix durability. The impermeable 14mm MA mix was chosen and a series of 150mm diameter test specimens prepared using a gyratory compactor with increasing number of gyrations used to give a range of void contents. To accelerate the effects the asphalt was subjected to oven aging prior to test specimen preparation and compared to unaged asphalt. The air void contents ranged from 13 to 23%. It should be noted that properly compacted test specimens for the asphalt used should have had a void content of 6 to 8%.

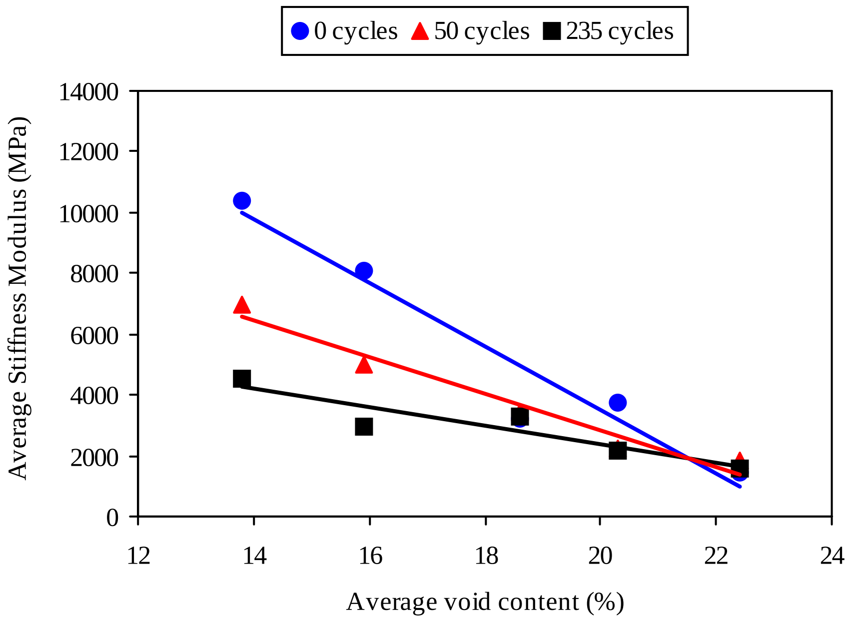

Figure 10. Relationship between Stiffness Modulus and void content for increasing number of rainfall cycles.

The Ulster Rainfall Simulator (URS) was modified to simulate repeated rainfall events using a digital timer at an intensity of 80mm/hour. The digital timer was used to produce 4 rainfall events over a 24 hour period. Each event lasted for 6 hours and consisted of 30 minutes rainfall and 5.5 hours drying at room temperature. The Indirect Tensile Stiffness Modulus (ITSM) in accordance with BS EN 12697-26 (2004) was used to assess the effect of repeated rainfall and drying events. The ITSM of each test specimen was assessed prior to simulated rainfall. After 7 days the test specimens were placed in the Nottingham Asphalt Tester (NAT) temperature control cabinet at 20°C for 16 hours. The ITSM was determined and the test specimen weighed. The aged asphalt data is plotted in Figure 10 and shows Stiffness Modulus to decrease with increasing number of rainfall cycles. It also shows a more complex relationship between void content, stiffness and number of rainfall cycles.

Figure 11 compares the average aged and unaged data in relation to number of rainfall cycles. For the same simulated rainfall conditions, the data shows a significant difference between the two sets of data i.e. the aged samples loose stiffness whereas the unaged well compacted samples are unaffected by rainfall.

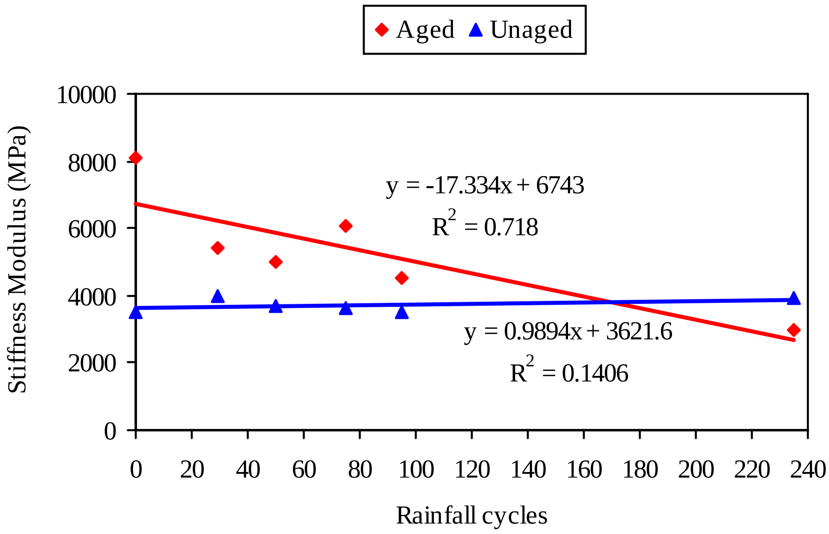

Figure 11. Comparison of aged and un-aged test data.

6 CONCLUSION

This paper summarizes a research project designed to consider three factors relating to the effect of rainfall on the performance of asphalt surface course materials i.e. rainfall runoff characteristics, road safety and mix durability. All three were found to be inter-related and have important implications in terms of safer road design.

For a single lane it will take approximately 50 to 200 seconds to reach equilibrium runoff conditions. For a multi lane highway it will take longer. After a rainfall event cross fall is important to drain away surface water and allow the surface to dry to maximize grip. A road with greater cross fall will allow a surface course with lower texture to be safer as the effect of the water will be reduced. Once the road surface gets wet, there is an almost immediate loss in skid resistance that may be significantly less compared to its dry condition. Based on pendulum measurement there was no further loss of skid resistance with increasing rainfall intensity until the surface was flooded when the pendulum was found to be unsuitable.

The RTM equipment subjected the laboratory prepared test specimens to simulated trafficking and showed how their dry and wet skid resistance properties and texture depth changed with time. Despite being typical specification requirements there was no correlation found between skid resistance and texture within the range of texture depth found for the surface materials tested. Therefore it is important to assess each property.

The effect of rainfall on the durability of road surface course materials was developed using the URS to simulate rainfall and drying out periods with its effect on mix durability quantified using the non-destructive ITSM test. For the 14mm MA material assessed it was found that accelerated aging of the mix prior to testing had a significant effect on the manufacture of test specimens, void content and initial Stiffness. Increasing number of rainfall cycles caused Stiffness to decrease for the aged test specimens. The unaged test specimens remained un-affected.

The dry-out test investigation showed that there is a distinct difference between the more impermeable materials (e.g. 10mm MA and 14mm MA) and the more permeable materials used (e.g. 6mm OT and 10mm DBM). Most of the mass loss for the 10mm and 14mm MA related to water trapped in the depth of its surface texture whereas a significant amount of water remained within the permeable 10mm DBM and 6mm OT after 7 days.

In conclusion, climate change predictions indicate that rainfall intensity and frequency will increase i.e. roads will be wetter for longer periods of time. Road surfaces loose skid resistance when they get wet i.e. they become more dangerous. Water can affect durability of road surface materials. In terms of reducing serious inquiry and fatal collisions the research has found that cross fall could be increased, speed limits reduced and more use be made of permeable materials.

Whilst it may be argued that these overall conclusions are obvious, the main finding of the research is that there are strong inter-relationships between surface course properties and research such as that reported in this paper is developing better laboratory predictive techniques that improve understanding of the processes involved.

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