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Decarbonisation of Local Roads & Highways Across The UK: Mechanical, Durability Properties and CO_2 Emission of a Smart Cold Mix Asphalt For Walkways, Cycle Path, Surface Course and Binder Course

ADEPT Live Labs 2 Liverpool

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March 2026

Contents

Executive Summary

As part of the ADEPT Liverpool Live Labs 2 Project, the Pavement Engineering Research Team at BEST (Built Environment and Sustainable Technologies) Research Institute at Liverpool John Moores University (LJMU) was selected to research and develop a novel fast-curing cold mix asphalt (HAN-CMA) to decarbonise local roads and support the transition to net zero carbon roads in the UK. The Liverpool John Moores University team also developed Low Heat Asphalt (HAN-LHA), where asphalt mixtures made at a temperature of 60°C, to enhance durability of the asphalt mixtures. Three different types of design mix asphalt were developed during this project complying with BS EN 13108 (2010), Table B.16 for 0/6 Asphalt Concrete (AC6), Table B.14 0/10 Asphalt Concrete (AC10), Table B.11 0/20 Asphalt Concrete (AC20).

This research project consisted of a laboratory testing programme to include the following tests road engineers always considers evaluating the asphalt mixtures performance.

- Indirect tensile stiffness modulus (ITSM), one of the materials mechanical properties ranking asphalt pavement materials in terms of their stiffness capacity.
- Wheel-tracking test, a test that has been used by numerous researchers to assess asphalt mixtures' resistance to rutting.
- Fatigue cracking is one of the main structural distress modes found in layers of bituminous road pavement because of the repeated application of traffic-induced stresses, which can lead to a substantial decrease in the serviceability of flexible pavements.
- Water sensitivity test, to assess the materials' performance when it comes to contact with water.
- Ageing test, to simulate 10 years of bitumen age hardening.
- Air void contents and density calculations, to ensure proper compaction which can reduce the risk of rutting and surface wearing.
- Leachate tests of the trial mixtures, to ensure that there are no hazardous heavy metals able to leach into the soil or water table below.

Followed by the construction of a 11 trial sections area to evaluate the performance of the modified Liverpool John Moores University cold mix asphalt (HAN- CMA) and Low Heat emulsified asphalt mixtures (HAN-LHA). Hint HAN = Hassan Al Nageim

Liverpool John Moores University and Stephen Williams & Son ltd, constructed two trail sections at Newsham Park Liverpool, UK, the first as a walkway where the surface course is made from AC 6 (six trial sections of 1m x 1.5 m each), and the second a cycle path where the surface course is made from AC 10 (five trial sections each of 1m x 1.5 m) , the binder course is made from AC 20.

The trial site was monitored over 9 months by LJMU Pavement Engineering Research team to include visual checks for monitoring surface wearing and any defects that might happen during their performance under the combined effects of weathers and traffic loading. Celtest ltd, accredited independent testing company conducted the required field tests to assess the trial performance in terms of.

1. Texture depth,
2. Skid resistance,
3. Hydraulic conductivity,
4. Extracting core samples for ITSM, density and voids verifications

A carbon emission calculation was also conducted in collaboration with Colas ltd to assess the environmental performance of the asphalt materials at the Newsham Park Trial Site.

Key findings

- All HAN-CMA mixtures (except AC6 + 10% rubber), AC6, AC10, and AC20, achieved ITSM values after 3 days of curing that exceeded the minimum thresholds typically accepted by road engineers, namely 500 MPa, 1500 MPa, and 2500 MPa, respectively. HAN-LHA mixtures demonstrate good long-term performance potential, but the initial early strength of HAN-CMA remains superior in ITSM performance.
- Both HAN-CMA and HAN-LHA, demonstrate rutting performance well within the recommended 4 mm limit for high-traffic road applications. However, HAN-LHA mixtures consistently show slightly better rut resistance than their HAN-CMA counterparts.
- Both HAN-CMA and HAN-LHA, demonstrate improved fatigue cracking resistance compared with the HMA. However, HAN-LHA mixtures consistently show slightly better fatigue cracking resistance compared to their HAN-CMA counterparts. The AC 6 with 10% rubber showed greatest resistance as the strain amplitude increased.
- HAN-CMA mixtures exhibit superior resistance to water sensitivity compared to conventional HMA. HAN-LHA mixtures demonstrate good resistance to moisture damage and, despite slightly lower initial stiffness compared to HAN-CMA.
- HAN-CMA mixtures exhibit a significantly greater increase in stiffness after long-term ageing compared to conventional HMA. HAN-LHA mixtures demonstrate excellent long-term curing and ageing characteristics, with greater relative stiffness gains than conventional CMA, despite lower initial stiffness.
- LJMU asphalt mixtures achieved air void contents within or close to acceptable industry ranges, suggesting generally adequate compaction and performance potential. However, mixtures incorporating rubber crumb showed significantly higher air voids, highlighting reduced compaction efficiency due to the material's elastic properties.
- The environmental analysis of the HAN-Filler used in HAN-CMA and HAN-LHA mixtures indicates no adverse environmental impacts.

- The volumetric patch test results show that sections with HMA surface courses consistently achieve macrotexture depths that meet UK specification requirements, HAN-CMA surface courses produced lower macrotexture values. This reduced texture depth is likely influenced by the application of a seal coat, which may have filled surface voids and limited macrotexture.
- HMA surface courses consistently achieved high Pendulum Test Values (PTV), In comparison, HAN-CMA surface courses exhibited lower initial skid resistance, with some values falling close to or below minimum recommended levels. Optimisation of HAN-CMA surface treatment, particularly the seal coat application, is recommended to enhance early-life skid resistance
- The ITSM results from the cored samples indicate variability in in-situ stiffness performance across the different mixtures. HAN-CMA mixtures outperformed their HMA counterparts, with AC10 HAN-CMA and AC20 HAN-CMA exceeding the target stiffness requirements and demonstrating higher modulus values than the corresponding HMA mixes. The discrepancies between laboratory and field results are likely influenced by factors such as compaction quality, environmental exposure, and sample disturbance during coring
- The cored samples from the trial sections exhibited lower bulk densities and higher air void contents compared to those produced under controlled laboratory conditions. This trend is consistent across both HMA and HAN-CMA mixtures and highlights the impact of field conditions on compaction quality.
- At the material level, HAN-CMA consistently achieves carbon reductions in the range of approximately 71% to 85% compared to equivalent HMA mixtures. The substitution of the binder course alone offers considerable benefits, highlighting this layer as a key opportunity for reducing embodied carbon. Additional savings can be achieved through the incorporation of RAP and rubber crumb; however, these benefits are highly dependent on transport distances and can be offset where haulage requirements are increased. Despite the effectiveness of HAN-CMA in reducing material-related emissions, transport remains the dominant contributor to overall carbon impact. This significantly limits the proportional reduction achievable through material substitution alone and emphasises the importance of optimising logistics and prioritising locally sourced materials.

What This Means For Councils

The results from the trial monitoring supported by the laboratory testing programme and the carbon assessment show that the HAN-CMA and LHA materials have suitability for road and pavement construction. The HAN-CMA material show excellent mechanical and durability performance compared to HMA. The LHA shows signs of increased durability with high performance in long age testing due to high aggregates bitumen coating; some further work needs to be conducted to improve the early stage curing mechanical performance of the HAN-LHA. Further work needs to be conducted to consider the AC HAN-CMA with 10% rubber crumb, as the testing results were inadequate compared to the other LJMU materials. Further development on the optimisation of the HAN-CMA seal coat is advised to increase the durability, early age ITSM and skid resistance. The HAN-CMA material showed great carbon emissions savings. At the material level, HAN-CMA consistently achieves life-cycle carbon reductions in the range of approximately 71% to 85% compared to equivalent HMA mixtures. This range will be 85-90% reduction in CO2 emission at the materials mixing, laying stages. This proves that the HAN asphalt materials are suitable for use in decarbonising local roads with outstanding achievements for the transition to net zero carbon roads in the UK. Please see the details conclusions and recommendations at the end f this report.

Project Concepts

The Liverpool John Moores University Team, led by Professor Hassan Al Nageim, has achieved an outstanding breakthrough through the Liverpool Live Labs 2 project, funded by the Department for Transport (DfT). The project is managed by Liverpool City Council in collaboration with Colas Ltd. As part of the ADEPT Liverpool Live Labs 2 programme, the BEST Research Institute (Built Environment and Sustainable Technologies) at LJMU was commissioned to research and develop a novel fast-curing cold mix asphalt (HAN-CMA), and Low-carbon Low heat asphalt mix asphalt (HAN-LHA). These ***new products*** aims to decarbonise local roads and support the UK's transition to net zero carbon road infrastructure.

In ***part one*** of this project, the LJMU research team developed a novel, high durability fast-curing cold-mix asphalt (HAN-CMA) for the walkways and road surface and binder course of a pavement design. The new Liverpool John Moores University cold mix asphalt has been made from a modified asphalt emulsion binder and an environmentally friendly binding filler. The filler is made from industrial by-products which behave as secondary cementitious materials (SCMs), replacing carbon intensive Ordinary Portland Cement (OPC) found in other fast-curing conventional CMA (Al Nageim, et. Al, 2012).

The new HAN- CMA and HAN-LHA, reduces CO_2 emissions during asphalt layers cycle fife by more than 70%-85% compared with conventional hot mix asphalt used in road structural layers. *Other advancements include developing asphalt from industrial by-products, Recycled Asphalt Pavement (RAP) and recycled rubber crumb to create more sustainable mixtures. Combining these products, methods of mixing and compaction, further lowers energy consumption and resultant carbon emissions.*

In **part two,** which is the second phase of the project will focus on a second novel asphalt developed by Liverpool John Moores University HAN-LHA. In this phase, the same HAN-CMA mixtures used in part one will be heated to a low temperature of 60°C during production. This controlled low-temperature process is intended to enhance the durability and compaction performance of the material, while still delivering significant carbon emission reductions compared with conventional, business-as-usual asphalt production methods.

Cold mix asphalt is a bituminous road construction material that is produced and applied without heating of the aggregates or bitumen emulsion binder. Commonly CMA is used for maintenance repairs for road surfaces or as construction materials for low traffic dense areas (Shanbara, H et al 2021). CMA is commonly used to fill potholes and cracks in our roads as temporary maintenance solutions, but its environmental properties make it an interesting solution to the decarbonisation of the roads in the UK and worldwide. CMA requires no heating during its production and is produced at ambient temperature. This means that very little CO2 and GHG emissions are emitted during its production, laying and compaction. Cold mix asphalt requires minimal heating, most of the production is done at ambient room temperature with no heating which results in considerable energy savings (Lu et al. 2013). Chappat and Bilal conducted research in 2003 which concluded that the fuel usage for hot mix asphalt was between 6.2-7.2 kg/ton and zero for cold mix asphalt. Their research also found that for each ton of hot mix asphalt manufactured 22kg of CO2 emissions were produced. For cold mix asphalt only 1 kg of CO2 emissions were produced per ton manufactured (Chappat and Bilal, 2003). This also makes CMA safer for producers and workers to work with compared to HMA where many health and safety risks are involved. This makes CMA a truly desirable product for the construction of roads in the UK.

The main problem when considering CMA for the construction of roads in the UK and worldwide is its mechanical properties. Many authors such as, M.A Kadhim (2022) and Thanya (2014) have reported that CMA has low early life strength, low durability and long curing times when compared to HMA (M.A Kadhim, 2022) (Thanaya, 2014). Research also shows that the addition of OPC can increase the curing time of CMA. Results from Thanya et al, shows that the addition 1-2% of cement can significantly accelerate the mechanical strength of CMA (Thanaya I, Zoorob S, Forth P. 2009). OPC has high embodied carbon and therefore is not a desirable product when focusing on the decarbonisation of local roads in the UK.

Efforts have explored the incorporation of waste and by-product materials such as steel slag, pulverized fuel ash (PFA), and crushed glass as supplementary cementitious materials to enhance cold mixes. In other words, these materials were used as partial replacements for ordinary Portland cement (OPC). Theoretically speaking, four main benefits can be achieved when utilizing waste or by-product materials on CBEM's: absorption of the trapped water via the hydration process, improvement in mixture mechanical properties, cost effectiveness and the ecological benefit factors. Unfortunately, these attempts fail to satisfy the EU and BS standards requirements in both their mechanical and durability requirements.

The main benefits of the HAN-CMA & HAN- LHA materials are;

- The carbon emission saving, this is due to the reduced energy consumption required for the heating of materials during mixing, laying and compaction compared to the traditional hot mix asphalt.
- Further carbon saving comes from the use of waste by-products materials as a secondary cementitious material (HAN-SCM) to replace the conventional

lime-stone filler in conventional HMA and used as filler in HAN- CMA and HAN-LHA to enhance the mechanical properties of the material instead of using OPC which is found in other researchers Dulaimi (2016) and Al Nageim (2012) modified cold mix asphalt.

- Another benefit of HAN-CMA and HAN-LHA bituminous material is that it's produced at ambient temperatures for HAN- CMA and at 60 °C for HAN-LHA. In UK and worldwide, the use of conventional CMA containing traditional limestone filler is largely restricted to surface treatment such as surface dressing, slurry surfacing, and reinstatement work on low trafficked and walkways. Thus, uses of CMA for structural layers are very limited, due to the long-time curing of the mix after laying (normally 2 months to 24 months) required such materials to reach their full strength after paving, especially in the UK climate (Head, 1974). Additionally the conventional CMA durability is very low because the combination of adhesion and viscosity of the asphalt binder in the CMA are very low.

The central theme of the work reported here concerns the use of,

i) High quality HAN- emulsion and

ii) Secondary Cementitious Material (HAN - SCM) produced from activated waste by-products.

Previous studies mentioned above prove that ordinary Portland cement, rapid setting cement and other additives improved the mechanical properties of CMAs, but they have the disadvantage of high cost and other related environmental impacts such as the high CO2 emission.

The HAN-CMA in this study incorporates a high percentage of activated waste by-products as a filler replacement in the mix. Filler contents normally equal to 6% of the aggregate weight as recommended by the BS EN 13108 for HMA (Hot Mix Asphalt). Outstanding improvement in mechanical properties of the new HAN-CMA and HAN- LH A containing HAN new bituminous emulsion and HAN -SCM activated fillers used in the trial as can be seen in the laboratory testing results of this report. Interestingly the visual monitoring of the trial sections from 3 days to 9 months shows that the HAN- CMA is providing excellent resistance to traffic loading in terms of wearing and weather in addition to providing surface water proofing material.

Background Studies: Hot Mix asphalt, Warm Mix Asphalt and Cold Mix Asphalt Background Summary

Hot Mix Asphalt (HMA)

Asphalt Pavement is a composite material that consists of two parts. The first part is the binder, which is the bitumen. The second part is the aggregate, usually made up from design graded coarse and fine aggregates and a filler with and without cementitious properties. Both parts are mixed together to create road surfaces and pavements. The bitumen behaves as the adhesive in the mixture and is referred to as a black cementitious solid which is derived naturally or manufactured (Anupam, K. *et al.* 2023). The aggregate is used to withstand the traffic loads whilst the bitumen provides the bonding to keep the material homogenous.

Hot mixed asphalt is used traditionally across the UK to construct the roads and highways. During the production of HMA a large amount of fossil fuels and greenhouse gases are emitted due to the required heating of aggregates at temperatures of around 170°C (H. Shanbara, 2021). To produce 1 tonne of HMA it requires around 300000 British thermal units, this is due to the required heating of aggregates, this process consumes large amount of fossil fuels between 7.6 and 11.4 L of fossil fuels and between 2.5 to 3.5 therms of natural gas (L.P. Thives, 2017). These emissions are detrimental to the environment, when released into the atmosphere the greenhouse effect is heightened, increasing the rate of global warming and climate change. Not only does the aggregates require heating but the bitumen binder also requires heating. The pure bitumen binder used in the production of hot mix asphalt requires heating at 140 °C to 160°C (H.K. Shanbara, 2018). Although HMA is not an eco-friendly mixture its justification is the mechanical properties that it possesses. Hot mix asphalt is one of the earliest recorded paving materials, due to its superior mechanical properties and durability (S. Dash, 2022). HMA is known for having increased strength in the early stages of curing. This allows for highways to be constructed quicker as the asphalt is ready to be driven on as soon as the mixture has cooled down. HMA also proves to have increased indirect tensile stiffness with little curing time which makes it further desirable for a road surface material. Health and safety procedures are also a concern when working with hot mix asphalt as the elevated temperatures make it a dangerous material to work with. The machinery used to compact and lay the asphalt require high skilled professionals to navigate them. These machines are also a health and safety hazard due to their size and weight. This is why a new safe and sustainable material is desired in the industry.

Warm and Half Warm Mix Asphalt

The temperature range for HMA is kept between 160°C and 200°C as any lower temperature would change the definition of the material. At 140°C this is where the product is defined as a warm mix asphalt pavement, and for halve warm asphalt the temperature reduced to approximately 120°C. Warm mix asphalt pavement does have significant reduction in energy consumption and therefore reduced greenhouse gas emission emitted in the production stage, but the performance may be hindered by this. Long term performance of warm and half warm mix asphalt is questioned due to a lack of research, and this could be the reason why majority of the European countries produce less than 10% of warm mixed asphalts (Ingrassia, L. et al. 2023). Additives can be added to the warm mix to ensure that there is an adequate workability rate at lower temperatures (Ferrotti, G. et al. 2024), these additives can also help improve durability, tensile strength and rutting resistance. To implement greener warm mix asphalt as a standard practice in road pavement design, more research is required and may offer a more sustainable future to the industry.

Cold Mix Asphalt

Cold mix asphalt, CMA, is more commonly used for roads surface repairs and maintenance. Its economic and environmental advantages make it a desirable mix to work with. Now that the UK government has set a target for net zero emissions by 2050 (GOV) the use of cold mix asphalt could be incorporated into larger scale construction of roads and highways in the UK. Cold mix asphalt does not require any heating during the process of heating, compacting or laying (Al Nageim et al, 2012). This is highly beneficial as minimal carbon emissions and other greenhouse gases are emitted during the lifetime of cold mix asphalt. This will therefore support the government's target and help reverse global warming and climate change. CMA using limestone filler for low traffic roads is rejected by many engineers due to its weak early mechanical life strength, high air void contents and reduced durability compared to HMA (M.A Kadhim, 2018). Another reason why the use of CMA is restricted is due to the amount of curing time it takes to reach an acceptable strength (S. Jain, 2021). Researchers have determined that cold mix asphalt can take from 2 to 24 months curing time (Dulaimi, 2017). Although cold mix asphalt has long curing periods there are many factors which can affect the mechanical properties of cold mix asphalt this can be the filler used, air void content, bitumen binder grade and aggregate type and gradation (H. Nageim et al, 2023). Many researchers are looking for a breakthrough in this material to enhance the properties to make them suitable for the construction of roads and highways in the UK. One method is to use cementitious fillers in the mixture, Head (1974) found that adding 1% OPC (ordinary Portland cement) increased the Marshall stability of mixes by 250%-300%. One researcher, Thanya found that adding 1-2% rapid setting cement increased the early strength of cold mix (Thanya, 2014). But OPC has high embodied carbon

Development of High Quality Cold and Low Heat Asphalt at LJMU

Pavement Engineering research team at LJMU has been investigating and developing the idea of creating CMA sustainable road materials for roughly 20 years. Led by Professor Hassan and his research team to include but not limited to, Anmar Dulaimi, Shakir Busaltan, Hayder Shanbara, Abbas AlHidabi, Manar Herez, have published numerous research papers investigating the development of ecofriendly bituminous materials. Some examples of these papers are, “the performance of half warm rolled mixtures” by Al-Hdabi, et al (2018), “High performance cold asphalt concrete mixture for binder course using alkali-activated binary blended cementitious filler” by Anmar Dulaimi et al, (2017), “Green Bituminous Asphalt relevant for highway and airfield pavement” by Shakir Busultan et al (2012).

Mechanical properties of bituminous pavement including stiffness modulus, permanent deformation and fatigue resistance are affected by many factors among them are properties and grade of binder, mixture void contents, curing time, aggregate characteristics, and additives. Attempts to improve cold mixes mechanical properties have been investigate by several researchers such as Head (1974) who had indicated that Marshall Stability of modified cold asphalt mix increased by 250–300% with the addition of 1% ordinary Portland cement (OPC) compared with un-treated mix. Oruc et al. [2007] conducted experiments to evaluate the mechanical properties of emulsified asphalt mixtures having 0–6% Portland cement. Their test results showed significant improvement with high Portland cement addition percentage; moreover, they suggested based on the study test results, that the cement modified asphalt emulsion mixes might be used as structural pavement layer. Thanaya et al. (2014) reported the test results of research on cold emulsion mixtures. They showed that the addition of 1–2% rapid-setting cement accelerated the earlier strength as well as improve the mechanical performance of the modified cold mixes.

Pouliot et al. (2003) conducted a study with the aim of understanding the hydration process, the microstructure, and the mechanical properties of mortars prepared with a new mixed binder made of a cement slurry and a small quantity of asphalt emulsion (SS-1 and CSS-1) (i.e. anionic and cationic emulsion). They proved that the presence of a small quantity of emulsion influenced the cement hydration. Their test results also indicated that the launch of asphalt droplets inside a cement mortar matrix leads to a considerable reduction in compressive strength and elastic modulus in addition to a slight decrease in flexural strength. In addition, they found that the cationic emulsion (CSS-1) in contrast with anionic emulsion (SS-1) shows higher mortars strengths and elastic modulus. Other study by Wang and Sha (2010) indicated that the increase of cement and mineral filler fineness has a positive impact on micro hardness of the interface of aggregate and cement emulsion mortar. Furthermore, they showed that the limestone filler affects hardness value is higher when compared with granite and granite fillers.

Recent attempts that have been made by LJMU researchers led by Professor Hassan Al Nageim (2012), Dulaimi (2016) and Al-Busaltan, (2012), successfully tried the use of waste and by-products materials to improve cold bituminous emulsion mixtures (CBEM), where the three main benefits could be achieved when utilising the by-product materials on CBEM's. Firstly, improving mechanical properties, in general there will be an enhancement of ultimate strength due to the cementitious properties of the added waste by-products materials. Secondly, gaining economic benefit as the pozzolanic and cementitious materials used with these materials to complete the hydration process are from waste products helped in getting rid of the excess water, which is the main reason of increasing the curing period in traditional cold mix asphalt containing Limestone fillers, and lastly, the ecological benefit factor.

As stated above, the central theme of the work reported here concerns the use of,

- High quality LJMU modified bitumen emulsion
- Secondary Cementitious Material (HAN-SCM) as a filler produced from activated waste by-products.

- Previous studies mentioned above prove that ordinary Portland cement, rapid setting cement and other additives improved the mechanical properties of CMAs, but they have the disadvantage of producing very stiff, brittle and less durable asphalt-concrete materials with high cost and other related environmental impacts such as the high CO2 emission.

Previous studies have shown that ordinary Portland cement (OPC), rapid-setting cement, and other cementitious additives can significantly improve the mechanical properties of cold mix asphalts (CMAs). However, these materials present notable drawbacks, including high cost and elevated CO_2 emissions associated with their production.

The LJMU CMA in this study incorporates a high percentage of activated waste by-products as a filler replacement in the mix namely (HAN-SCM). Filler contents normally equal to 6% of the aggregate weight as recommended by the BS EN 13108 for HMA (Hot Mix Asphalt). Outstanding improvement in mechanical properties of the new HAN-CMA containing HAN-Phalt a new bituminous emulsion and HAN-SCM activated fillers used in the trial as can be seen in the laboratory testing results of this report. Interestingly the visual monitoring of the trial sections from 3 days to 9 months shows that the HAN- CMA is providing excellent resistance to traffic wearing and weather in addition to providing surface water proofing material.

Material used in this study: Aggregates

For this project three aggregate gradation types were used. AC dense surf 6, AC close surf 10 and AC dense surf 20. The virgin aggregate was made up from crushed granite. The gradation for these aggregates was confirmed via the sieve test in accordance with BS EN 13108 (2015).

Sieve Test: Figures 1 to 3

The figures show the aggregate gradation specifications for AC 6 Dense Surf, AC 10 Close Surf, AC 20 Dense Surf, respectively following BS EN 13108, Bituminous mixtures – material specifications (2015). The figures show the percentage of cumulative weight of each aggregate sizing within the mixture, showing the design parameters of each sample.

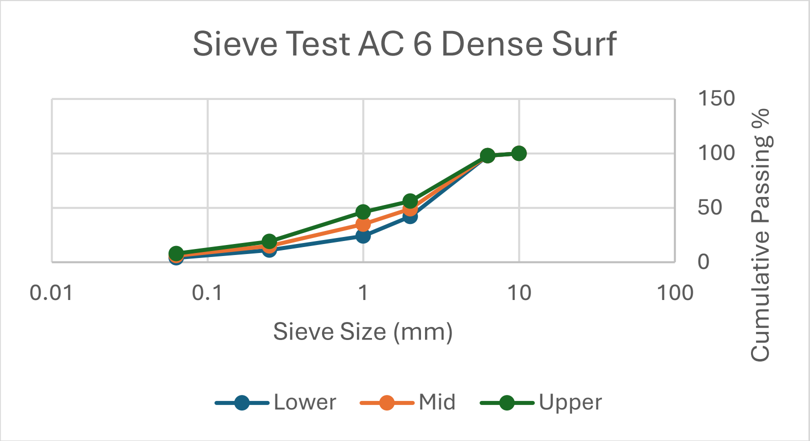

Figure 1. Sieve Test for AC 6 Dense Surf

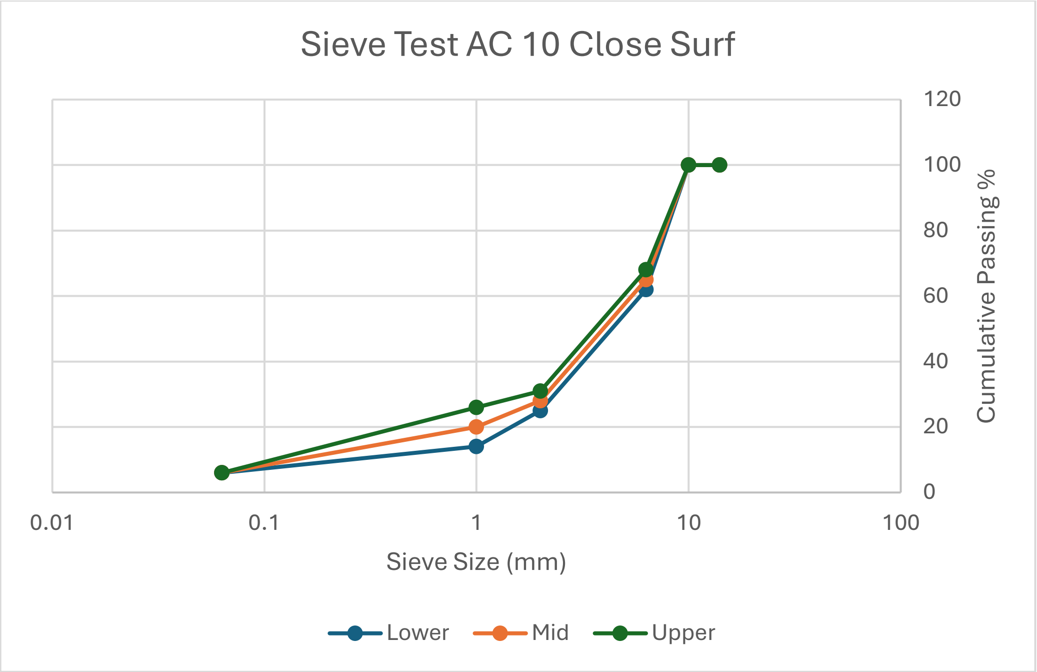

Figure 2. Sieve Test AC 10 Close Surf

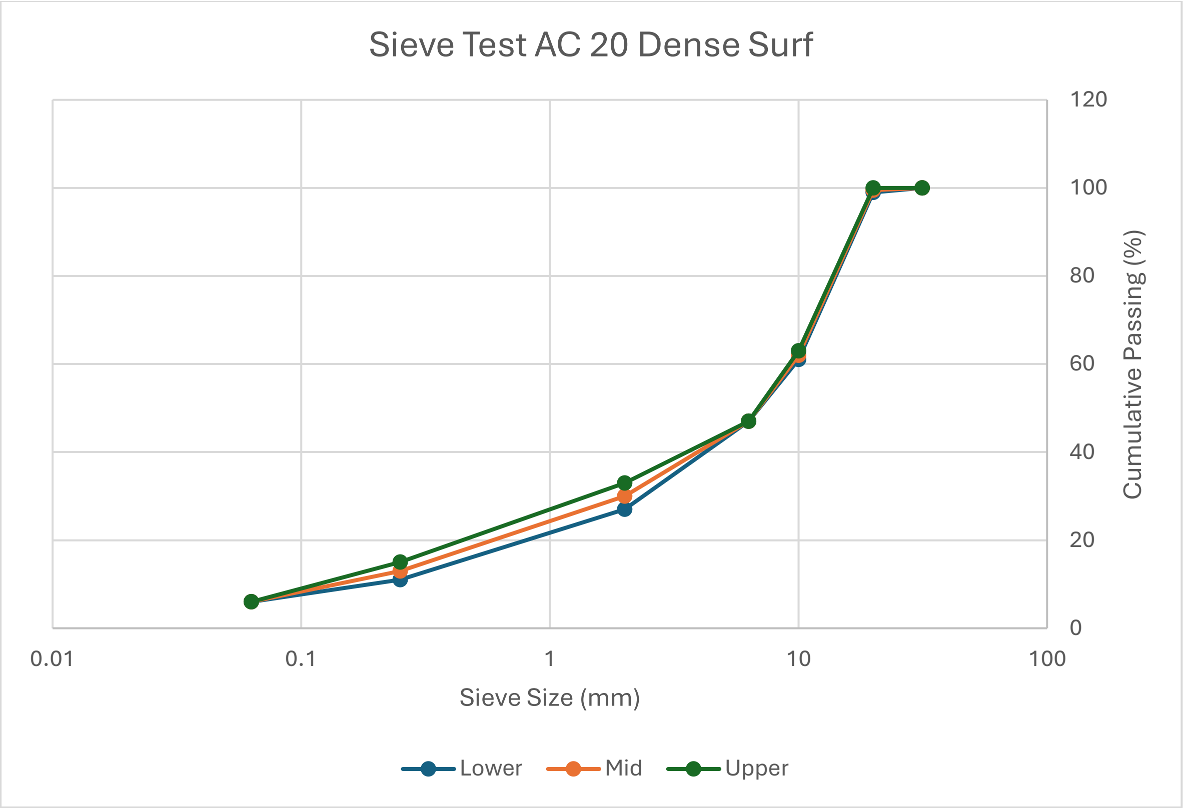

Figure 3. Sieve Test for AC 20 Dense Surf

Recycled Asphalt Pavement (RAP)

RAP is recycled or reclaimed asphalt pavement, the aged aggregate and binder can be utilised and reused at the end of its life to produce new pavement (Han, S. et al. 2019). This helps reduce the need for virgin aggregates and binders to be produced. This results in a reduced amount of aggregate being quarried by high fuel consuming machines. This also reduces the fuel consumed from the transportation of the aggregates. All of this reduces the greenhouse gases emitted from the sourcing of materials. Research shows that a combination of reduced temperatures and inclusion of RAP of 10-50% in traditional hot mix asphalt can reduce the total greenhouse gas emissions by 12-17% (Vidal, R. et al. 2013). When using RCA, recycled aggregate a saving of 65% greenhouse gas emission has been found compared to using virgin materials (Uzzal Hossain, M. et al. 2016). Not only does using RAP reduce greenhouse gas emissions, but it also reduces the amount that goes to landfills, this therefore benefits the environment by reducing chemicals leaching into the soil which causes pollution. Engineers tend to use a smaller percentage of RAP in design due to the unpredictable gradation size and asphalt content (Xioa, F. et al. 2023).

The RAP used in the laboratory testing programme was provided by Colas ltd, UK. The RAP was added as a 20% replacement for the virgin granite aggregates to the binder course. This percentage was chosen by Professor Hassan Al Nageim, from his experience in the industry and from literature found in research papers globally.

Fine Rubber Crumb

The rubber crumb used in this project was rubber crumb dust below 1mm. Crumb rubber is a term usually applied to recycled rubber from scrap tires of heavy goods vehicles. Crumb Rubber is made from selected waste tire which no longer be contaminated by steel wire or nylon (Wulandari, P et al. 2019). The rubber was used as a replacement of fine material within the LJMU AC 6 Mixtures to provide the following advantages; improved flexibility to reduce cracking, smoother and quieter road surfaces and environmentally sustainable by recycling waste tyres and reducing quarrying for virgin aggregates (Wulandari, P et al. 2019).

Filler

Traditionally, limestone filler is used in CMA, but due to CMA low early age strength, high air void content and high-water sensitivity, Ordinary Portland Cement (OPC) is often added to enhance their mechanical strength and durability of the mix (Lu, D. et al. 2021), However, OPC production is associated with significant carbon emissions. It has been estimated that the manufacture of OPC produces approximately 0.66–0.82 kg of CO_2 per kilogram of cement produced and contributes around 5–7% of total global anthropogenic CO_2 emissions (Huntzinger and Eatmon, 2008). The high embodied carbon of OPC is primarily attributed to the calcination of limestone during the production process, where materials are heated to temperatures of approximately 1400 °C, releasing large quantities of CO_2 (Gartner, 2004).

In order to reduce the overall CO2 emissions of the LJMU asphalt mixes, LJMU Filler was developed in the LJMU laboratory by using a combination of treated environmentally friendly natural and industrial by products waste materials which behave as secondary cementitious materials (SCMs). The HAN-SCM Filler contributes to the strength development of the asphalt mixture through chemical activation and hydration reaction that occurs between the filler and the water present in the bitumen emulsion. The water from the bitumen emulsion reacts with the HAN-SCM filler, producing cementitious hydration products, while the progressive loss of water allows the bitumen emulsion to break and the bitumen emulsion droplets to coalesce. This forms stronger adhesion between the aggregates in the mix allowing for an overall increased strength and more durable asphalt mixture.

Bitumen Emulsion

Bitumen emulsion is the mixture of bitumen and water with an emulsifying agent, which is commonly used as the binder material for cold mix asphalt materials for the maintenance of highways in the UK (Shanbara, H. *et al*. 2021). Bitumen emulsions are used when aiming to reduce energy consumption of an asphalt material, where pure bitumen requires heating of 140°C-160°C (Querol, N., Barreneche, C. and Cabeza, L. 2017). Using bitumen emulsion to produce CMA is desirable due to the low embodied carbon.

The bitumen emulsion was sourced from Jobling Purser, a highway maintenance product company based in Newcastle. The company have been creating bitumen emulsion since 1920. The emulsions used were as follows.

The EM 48, is a fast breaking, low tack, high strength bond coat for bituminous surfacing materials, in compliance with the Specification for Highway Works- Clause 920 and BS EN 594987. The modified binder provides enhanced cohesion for optimal inter-layer bond strength and reduced temperature susceptibility, while the low-tack attribute reduces pick-up by construction traffic.” (Jobling Purser. 2024)

The bitumen emulsion provided from Jobling Purser was then developed further in the LJMU laboratory by adding HAN-additive to the emulsion to increase adhesion within the asphalt mixture and increase the overall durability of the new emulsified asphalts (HAN-CMA and HAN-LHA). The additive improved the workability of both HAN-CMA and HAN-LHA asphalt mixtures, resulting in improved compaction leading to a longer life span. Without the addition of the additive the mixtures become brittle, leading to cracking and asphalt failure.

Laboratory Testing Programme

Table 1, shows the Laboratory Testing Programme, performed on all the asphalt mixture created in this project and according to the current BS EN standards procedures.

Table1: Laboratory Testing Programme,

Indirect Tensile Stiffness Modulus
Indirect Tensile Stiffness Modulus – Conditioned
Rutting Resistance – Wheel Track Test
Fatigue Crack Resistance – Four-Point Bending Test
Indirect Tensile Stiffness Modulus – Ageing
Water Sensitivity
Air Void Contents
Measured Bulk Density
Leachate of Heavy Materials

Details of Trial Sections: Newsham Park Trial, Liverpool, UK

Working alongside Liverpool City Council and Henry Williams and Son ltd, the trial sections were completed over a period of 8 days. The trial sections were split into two functions; the first trial was to behave as a walkway and the second trial to behave as a cycle path. Each Trial was split up into sections of 1.5 meters in length and 1meter width.

The binder course for the trials was made from 3 types of 0/20mm asphalt concrete (AC) mixtures at a depth of 50mm which was used on both trials. The first type was the traditional HMA which was heated over 160°C with bitumen which has a penetration grade of 40/60. The second type was the HAN-CMA which is modified to enhance the mechanical and durability of the material. The third type is the HAN-CMA with 20% RAP. The RAP helps to decrease the carbon footprint further by reusing recycled road materials, see table 1 below.

For the first trial,' the walkway', AC 6 surface course was used, satisfying British standards (BS EN 13108 PD 6691:2015, Bituminous mixtures – Material). For this we used 3 different types of AC 6. Once again, we used a traditional AC 6 HMA made from 100/150 penetration grade bitumen, used as the 'control' section of the trial. This allows us to compare the HMA with the HAN- CMA. The second type is the AC 6 HAN- CMA which includes a modified bitumen emulsion together with HAN-SCM hydraulically bound filler which enhances the mechanical and durable properties of the material. The third type is the HAN-CMA with 10% of rubber crumb. The recycled fine rubber crumb is added to further reduce the CO2 emissions and enhance some of the durability properties of the material.

The second trial, 'the cycle path', used AC 10 for the surface course. This is due to expected higher traffic loading. Once again, a 'control' section was used made from AC 10 HMA made from 100/150 penetration grade bitumen. The other surface course was made using the AC 10 HAN-CMA for surface course and AC20 HAN-CMA for binder course.

Trial subsections performance was visually inspected at age of 0 days, 22 days 3 and 9 months. Further visual inspections will be conducted on 9 and 12 months

All of the asphalt mixture designs were following in accordance with British Standards (BS EN 13108 and PD 6691:2015, Bituminous mixtures – Materials).

Table 2, shows the cross section of the Newsham Park Trial, Liverpool , UK

Asphalt layers	Trial section 1. AC 6 for a Walkway						
	Thickness	Mix type					
Surface course	25 mm	AC6 HMA	AC6 HMA	AC6 HMA	AC6 CMA	AC6 CMA	AC6 CMA + 10% Rubber dust
Binder Course	50mm	AC20 HMA	AC20 CMA	AC20 CMA + RAP	AC20 HMA	AC20 CMA + RAP	AC20 CMA
Length of each section = 1.5m							
Asphalt layers	Trial section 2. AC10 for a Cycle Path						
	Thickness	Mix type					
Surface course	40 mm	AC10 HMA	AC10 HMA	AC10 HMA	AC10 CMA	AC10 CMA	
Binder Course	50mm	AC20 HMA	AC20 CMA	AC20 CMA + RAP	AC20 HMA	AC20 CMA + RAP	
	Length of each section = 1.5m						

Trial 1: Walkway Trial

Section 1: 1.5m in length, 25mm layer of 0/6 AC HMA surface course on 50mm layer HMA binder course
Section 2: 1.5m in length, 25mm layer of 0/6 AC HMA surface course on 50mm layer 0/20 AC HAN-CMA binder course
Section 3: 1.5m in length, 25mm layer of 0/6mm HMA on 50mm 0/20 AC layer HAN-CMA binder course with RAP

Section 4: 1.5m in length, 25mm layer of 0/6 AC HAN-CMA on 50 mm layer HMA binder course,
Section 5: 1.5m in length, 25mm layer of 0/6 AC HAN-CMA on 50 mm layer CMA binder course with RAP,
Section 6: 1.5m in length, 25mm layer of 0/6 AC HAN-CMA with 10% fine rubber on 50 mm layer HAN-CMA binder course

Figure 4. Trial 1, Walkway surface conditions

The sections are in order from section 1 to section 6 (left to right). Each section is separated by the white sections seen in the figure above. The trial sections surface conditions show high quality at all inspections on 3 days, 6 months and 9 months. Further visual inspection will be carried out at 12, and 24 months.

Trial 2: Cycle Path

Section 1: 1.5m in length, 40mm layer of 0/10 AC HMA on 50mm layer AC 0/20 HMA binder course

Section 2: 1.5m in length, 40mm layer of 0/10 AC HMA on 50mm layer AC 0/20 HAN-CMA binder course

Section 3: 1.5m in length, 40mm layer of 0/10 AC HMA on 50mm layer AC 0/20 HAN-CMA binder course with 20% RAP

Section 4: 1.5m in length, 40mm layer of 0/10 AC HAN-CMA on 50 mm layer AC 0/20 HAN-CMA binder course

Section 5: 1.5m in length, 40mm layer of 0/10 AC HAN-CMA on 50 mm layer AC 0/20 HAN-CMA binder course with 20% RAP

Figure 5. Trial 2, 'Cycle Path' surface sections

Figure 5 and 6 shows for the ‘cycle path, the second trial, sections 1-5 , the sections are in order from section 1 to section 5. Each section is separated by the black sprayed sections seen in the figure.

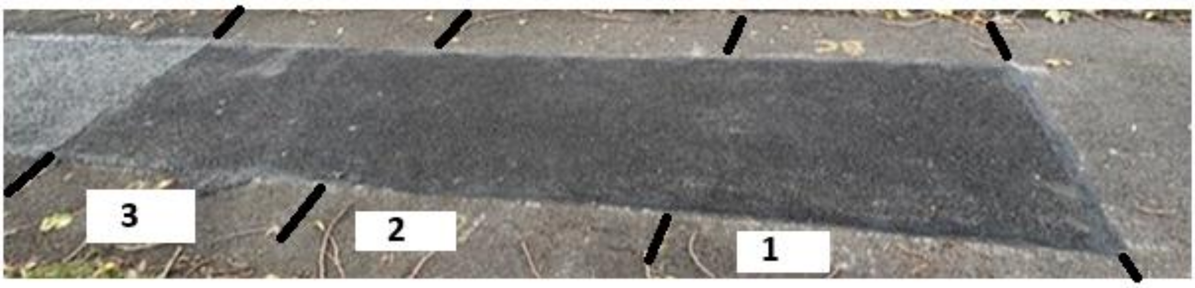

Figure 6. Cycle Path HMA surface conditions

and

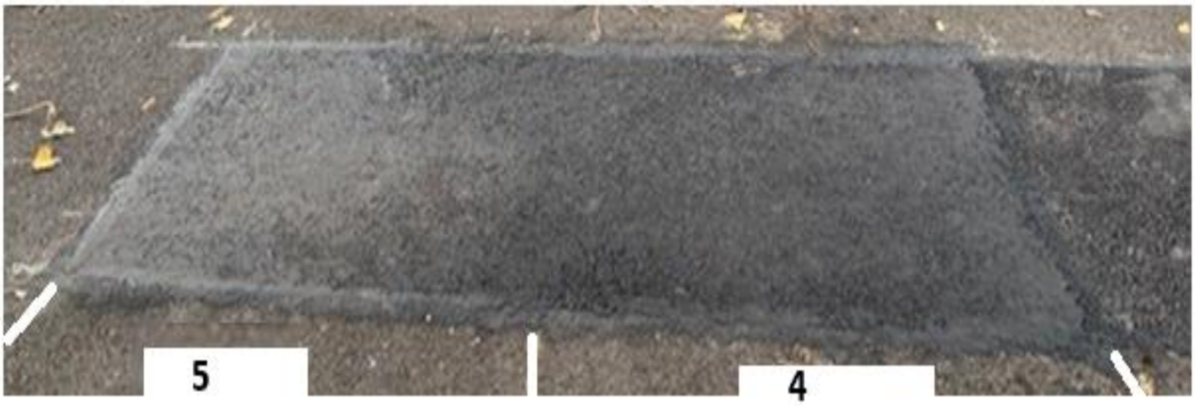

Figure 7. Cycle Path CMA surface conditions

Test Result, Analysis and Discussion

Liverpool John Moores University Laboratory Testing

Indirect Tensile Stiffness Modulus (ITSM)

The tensile stiffness of the bituminous asphalt mixes is correlated to the materials ability to distribute traffic loads which determines the materials cracking potential. ITSM testing is also used as an indicator towards the overall structural performance of the bituminous material (Dulaimi *et al.* 2017). The indirect tensile stiffness modulus test is used by many researchers, such as, Dulaimi (Dulaimi *et al.* 2017) and Al Hdabi (Al-Hdabi. 2018) as the test is completed quickly, it's non-destructive and it's considered one of the most significant characteristics of bituminous pavements.

Figure 8. ITSM Apparatus

The indirect tensile stiffness modulus testing was following in accordance with BS EN 12697-26 (CEN, 2012) using the Cooper Research Technology HYD 25 testing machine to carry out testing on the cylindrical specimens. The samples are produced following the Marshall method and demoulded after 24hrs. The samples are left to cure in the laboratory at 20°C until testing is required at 3,7,14,28 and 90 days of curing. ITSM is determined by applying five repeated loads, preceded by a preloading of 5 repetitions of load, which has the function of correcting the load application system to the sample. All ITSM tests were conducted at 20°C, with the samples conditioned for 4hrs prior to ensure the test temperature as stipulated in BS EN 12697-26 (CEN, 2012). In the table below you will find the conditions for testing.

Table 2. ITSM Test Conditions

Parameters	Range
Specimen diameter (mm)	100 ±3
Rise time (ms)	124±4
No. of conditioning pulse	5
Transient peak horizontal loading (µm)	5
Poisson's ratio	0.35
No. of test pulse	5
Test Temperature (°C)	20±0.5
Specimen thickness (mm)	63±3
Compaction	Marshall 50 blows/face
Temperature conditioning	4 hours before testing

To simulate field curing conditions, Ruckel et al. (1983) recommended curing specimens at 40 °C for varying durations. Intermediate curing conditions can be simulated by curing samples for 1 day at 40 °C, while long-term curing is represented by curing samples at 40

°C for 3 days. In this study, the "conditioned" ITSM specimens were cured at 40 °C for 24 hours after de-moulding to represent intermediate field curing conditions. This conditioning also provides an indication of the material's performance under elevated temperatures, offering insight into how the mixture may perform in warmer climates.

HAN- CMA Results

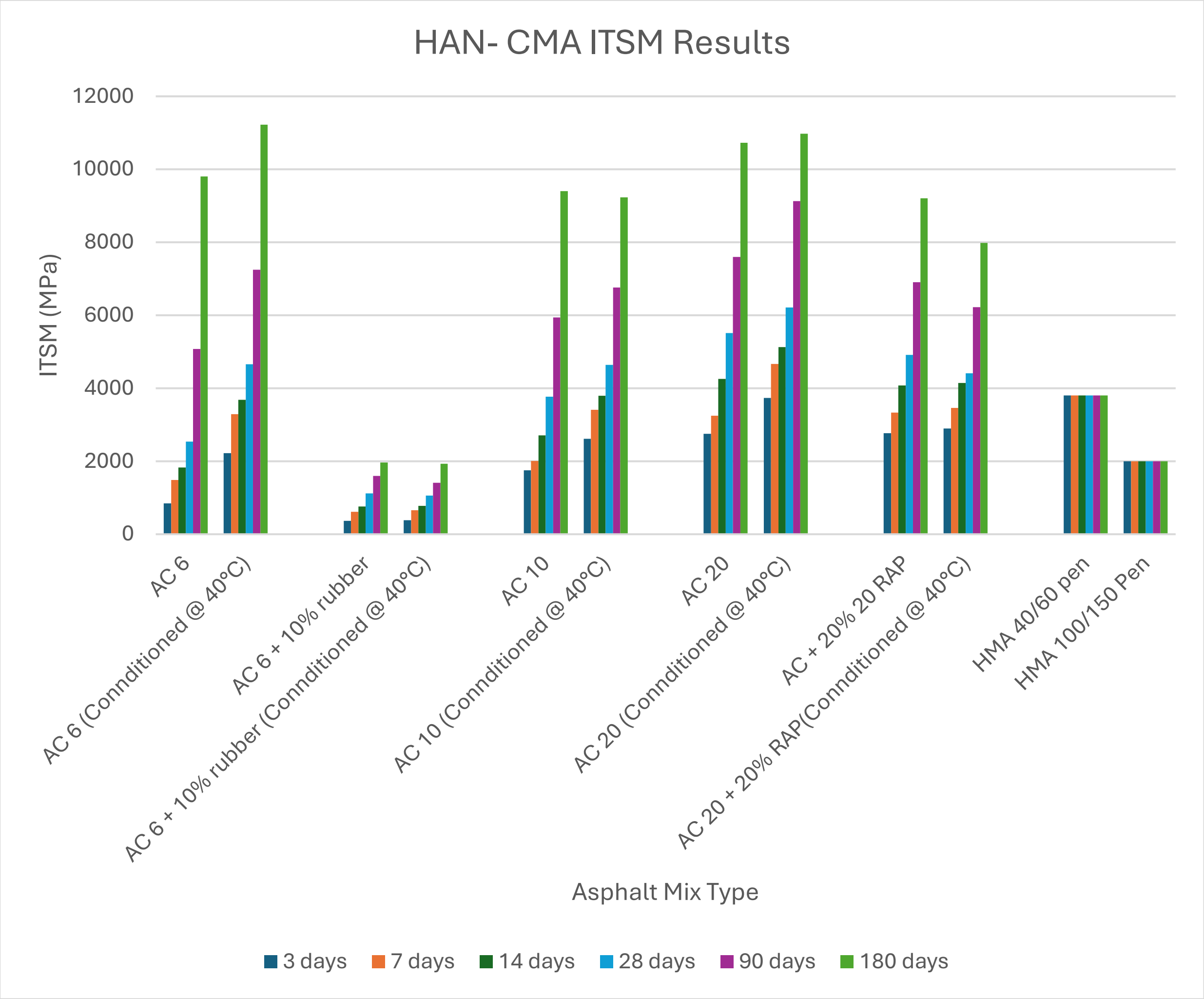

Figure 9. ITSM Results of the CMA samples

Figure 9. above shows results the Indirect Tensile Stiffness Modulus for HAN-CMA across 180 days.

LJMU AC 6 CMA Results

The minimum ITSM target for the AC 6 samples is 500 MPa. This value is acceptable for road engineers for low-trafficked surface course applications such as footways, footpaths, and cycle tracks. Figure 5 shows the ITSM results for the AC 6 HAN- CMA. After 3 days curing, the AC 6 HAN-CMA shows an ITSM of 850 MPa for the unconditioned samples and 2200 MPa for the conditioned samples. This satisfies the minimum ITSM target of 500 MPa, making the AC 6 suitable for low-trafficked applications after 3 days curing. Once again, the ITSM stiffness continues to increase alongside curing time, resulting in,

- At 7 days curing, approximately 1500 MPa for the unconditioned samples and approximately 3300 MPa for the conditioned samples.
- At 14 days curing, approximately 1830 MPa for the unconditioned samples and approximately 3700 MPa for the conditioned samples.
- At 28 days curing, approximately 2550 MPa for the unconditioned samples and approximately 4650 MPa for the conditioned samples.
- At 90 days curing, greater than 5000 MPa for the unconditioned samples and approximately 7250 MPa for the conditioned samples.
- At 180 days curing, approximately 9800 MPa for the unconditioned samples and greater than11,200 MPa for the conditioned samples.

The AC 6 HAN- CMA samples meet the minimum ITSM target of 500 MPa after 3 days curing, satisfying the requirements for low-trafficked surface courses. The conditioned samples show significantly higher early stiffness due to accelerated curing at 40°C, which promotes moisture loss and faster strength development. As curing progresses, both conditioned and unconditioned samples demonstrate substantial increases in stiffness, indicating strong long-term performance. These results confirm the suitability of AC 6 HAN-CMA for walkway and cycle path applications.

AC 6 HAN-CMA + 10% Rubber CMA Results

The AC 6 samples with the addition of 10% rubber was a new area of research for LJMU. From reading academic literature, the research into adding fine rubber crumb to CMA was limited. This meant that the LJMU team based their research on HMA adding rubber as a dry process. Following this method led the team to adding 10% of rubber crumb by dry weight to the mixture, from looking at figure 3. we have assumed that the rubber content is too high. The results fail to satisfy the minimum ITSM target of 500MPa after 3 days, the ITSM result show 365 MPa for the unconditioned sample and 385MPa for the conditioned sample. The low ITSM result is likely due to high quantity of rubber dust, the high elasticity of the rubber and increased void contents. The ITSM results do increase along with the curing,

- 7 days of curing see the ITSM results of 615MPa for the unconditioned samples and 660MPa for the conditioned samples.
- 14 days of curing see the ITSM results of 757MPa for the unconditioned samples and 777MPa for the conditioned
- 28 days of curing see the ITSM results of 1117MPa for the unconditioned samples and 1057MPa for the conditioned samples.
- 90 days of curing see the ITSM results of 1597MPa for the unconditioned samples and 1412MPa for the conditioned samples.
- 180 days of curing see the ITSM results of 1963MPa for the unconditioned samples and 1935MPa for the conditioned samples.

The AC 6 HAN- CMA with 10% rubber samples meet the minimum target of 500MPa after 7 days curing and continue to grow. Interestingly the conditioning doesn't have an effect on the ITSM results showing minimal differences between the unconditioned and conditioned samples. This material could be used for playgrounds/parks due to the high elasticity of the material reducing the risk of injury to children falling. We advise that the amount percentages of the rubber is to be revised and the rubber content is reduced to increase the ITSM results to be suitable for walkways opening at a shorter time.

AC 10 HAN-CMA Results

The minimum ITSM target for the AC 10 samples is 1500MPa, this value is acceptable for road engineers for a moderately trafficked surface course material. Figure 5 shows the ITSM results for the AC 10 HAN-CMA. After 3 days curing the AC 10 show ITSM of 1750MPa for the unconditioned sample and 2600MPa for the conditioned sample. This satisfies the minimum ITSM target of 1500MPa, making the AC 10 suitable for moderately trafficked roads after 3 days curing. Once again, the ITSM stiffness will continue to increase alongside the curing time resulting in,

- At 7 days curing, 2000MPa for the unconditioned samples, 3400MPa for the conditioned samples.
- At 14 days curing, 2700MPa for the unconditioned samples, 3800MPa for the conditioned samples.
- At 28 days curing, 3750MPa for the unconditioned samples, 4650MPa for the conditioned samples.
- At 90 days curing, 5950MPa for the unconditioned samples, 6750MPa for the conditioned samples.
- At 180 days curing, 9400MPa for the unconditioned samples, 9250MPa for the conditioned samples.

The AC 10 HAN-CMA samples meet the minimum ITSM target of 1500MPa after 3 days curing, satisfying the road engineers requirements. At 7 days curing the LJMU AC 10 ITSM results show the same results as the Hot Mix Asphalt (HMA) with 100/150 pen (The HMA with 100/150 penetration grade bitumen is what was used for the surface course trial section at Nesham Park). After 14 days curing the AC 10 HAN-CMA exceeds the ITSM results of the HMA, proving its suitability for road surfacing.

LJMU AC 20 CMA Results

The AC 20 HAN-CMA is used as the binder material for road construction design. The binder course sits beneath the surface course and above the base, demanding high strength to bare the traffic load. The minimum ITSM target for this is 2500MPa.

- At 3 days curing, 2750MPa for the unconditioned samples, 3750MPa for the unconditioned samples.
- At 7 days curing, 3250MPa for the unconditioned samples, 4650MPa for the conditioned samples.
- At 14 days curing, 4260MPa for the unconditioned samples, 5130MPa for the conditioned samples.

- At 28 days curing, 5500MPa for the unconditioned samples, 6200MPa for the conditioned samples.
- At 90 days curing, 7600MPa for the unconditioned samples, 9150MPa for the conditioned samples.
- At 180 days curing, 10700MPa for the unconditioned samples, 11000MPa for the conditioned samples.

The AC 20 HAN-CMA Samples meet the minimum required ITSM results of 2500MPA after 3 days of curing. The unconditioned samples had similar stiffness to HMA 40/60 pen (The HMA with 40/60 penetration grade bitumen is what was used for the binder course trial section at Nesham Park) after 14 days curing but continued to surpass HMA after 28 days. The conditioned samples ITSM results are similar to HMA after 3 days curing. This proves that AC 20 HAN-CMA is suitable as a binder material for road construction.

LJMU AC 20 + 20% RAP HAN- CMA Results

20% of Recycled Asphalt Pavement (RAP) was added to the binder course in order to further reduce the CO2 emissions of the mix design. Using RAP reduces the amount of quarried virgin aggregate required for the asphalt mix and therefore reduces the carbon footprint of the materials. The Minimum ITSM requirement is 2500MPa. Figure 3 shows,

- At 3 days curing, 2750MPa for the unconditioned samples, 2900MPa for the unconditioned samples.
- At 7 days curing, 3330MPa for the unconditioned samples, 3450MPa for the conditioned samples.
- At 14 days curing, 4080MPa for the unconditioned samples, 4150MPa for the conditioned samples.
- At 28 days curing, 4900MPa for the unconditioned samples, 4400MPa for the conditioned samples.
- At 90 days curing, 6900MPa for the unconditioned samples, 6200MPa for the conditioned samples.
- At 180 days curing, 9200MPa for the unconditioned samples, 8000MPa for the conditioned samples.

The main difference between the AC 20 and the AC 20 with RAP is that the conditioning does not have as much of an effect on the ITSM result. Although the initial ITSM results still increase after conditioning this is by a small value. By 28 days curing the unconditioned samples have a greater stiffness than the conditioned samples. This is due to the continuous hydration of the SCM and less to the aged bitumen found on the recycled aggregates that have already reached their peak stiffness. This is also the reason why after 180 days curing the AC 20 has much higher ITSM results compared with the AC 20 with RAP.

LJMU HAN-CMA ITSM : Comparison with XAIS-PTS Independent Laboratory Results

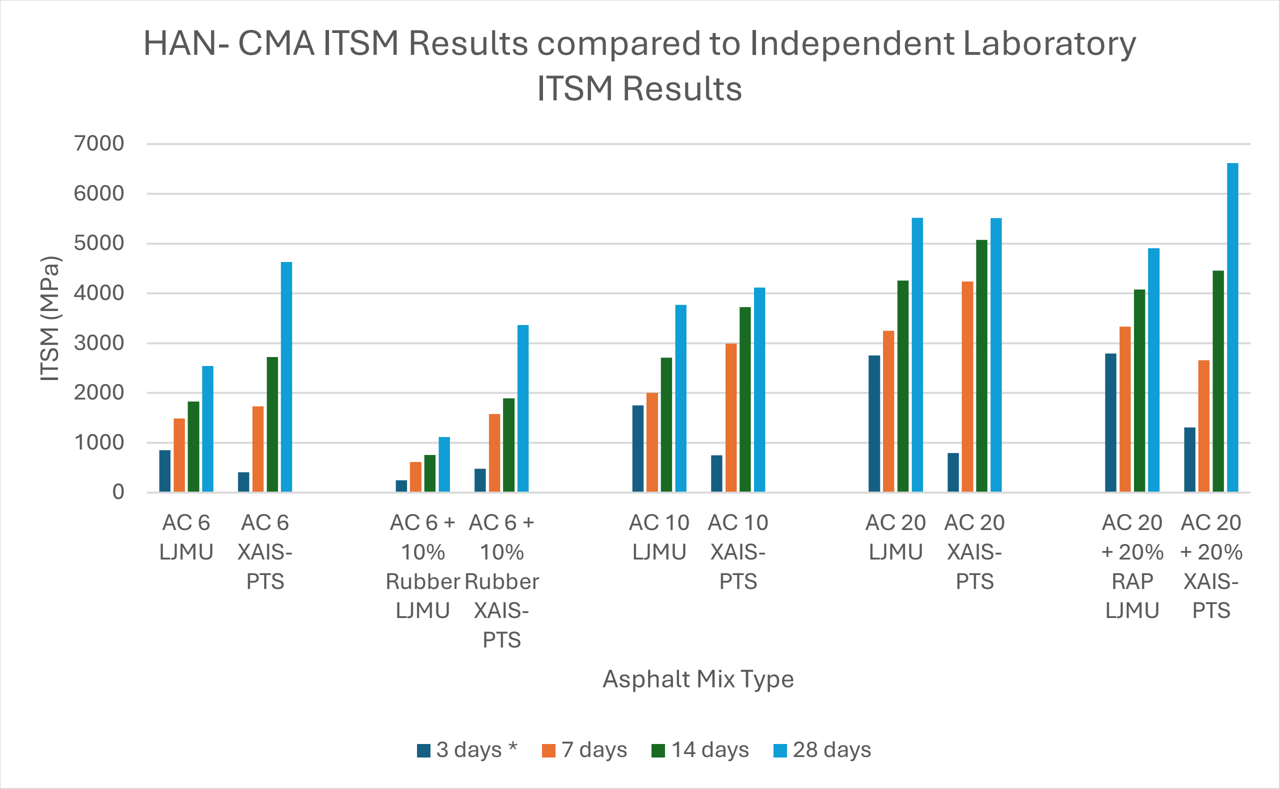

Figure 10. LJMU CMA ITSM Results compared to XAIS-PTS Independent Laboratory Results

Note: The HAN-CMA samples were sent to an independent laboratory, XAIS-PTS in Preston, for quality assurance and verification of results. Due to time constraints and shift patterns, the independent laboratory could not test the original samples for 3 days testing. This is why 3 days has an asterisk symbol; these samples were sent separately months later for their 3-day ITSM results. The results from the laboratory were only done over a 28-day curing and testing period.

AC 6 HAN-CMA Results

The results for AC 6 show a significant reduction in stiffness at 3 days from the samples tested at XAIS-PTS independent laboratory. The ITSM results from XAIS-PTS is, 410MPa which is below the 500MPa target for AC 6 HAN-CMA materials. This discrepancy may be due to two factors. First, the second batch sent to the independent laboratory was produced using the same control emulsion but after a significantly longer storage period than the samples tested at LJMU. The storage time exceeded three months. During this period, the emulsion may have undergone natural settlement and partial separation of the bitumen binder from the water phase. Although the emulsion is typically shaken and remixed using a shear mixer before sample preparation, prolonged storage may still affect its properties. That separation could be the main reason for the low ITSM at 3 days of age. Also, the diagram shows results substandard to the original set of samples which were not tested at 3 days curing. The ITSM results from the LJMU laboratory more than doubles the ITSM of the independent lab at 3 days. After the 3 days the results of the independent laboratory surpass the results of the LJMU lab,

- 7 days, the independent laboratory give an ITSM result of 1730MPa and the LJMU laboratory give a result of 1500MPa.
- 14 days, the independent laboratory give an ITSM result of 2720MPa and the LJMU laboratory give a result of 1830MPa.
- 28 days, the independent laboratory give an ITSM result of 4630MPa and the LJMU laboratory give results of 2550MPa.

The above results support our explanation on why the ITSM tested at the independent lab are lower than LJMU ITSM results at 3 days. This means the emulsion suffers segregation of water and bitumen binder due to the long storing in the lab.

LJMU AC 6 with 10% rubber HAN-CMA Results

The ITSM results from the independent laboratory show higher values for the AC 6 HAN-CMA with 10% rubber CMA than those obtained in the LJMU laboratory throughout the testing period. At 3 days, the independent laboratory recorded ITSM values almost double those measured by LJMU. The independent laboratory reported a stiffness of 480 MPa, while the LJMU results showed an ITSM of 250 MPa. This indicates that the independent laboratory results are close to meeting the target stiffness of 500 MPa after 3 days of curing. This trend continues throughout the testing period,

- 7 days, the independent laboratory shows ITSM results of 1575MPa and the HAN-CMA shows ITSM results of 615MPa. Where both testing facilities reach the 500MPa minimum target line for the AC6 surface course.
- 14 days, the independent laboratory shows ITSM results of 1900MPa and the HAN-CMA shows ITSM results of 750MPa.
- 28 days, the independent laboratory shows ITSM results of 3350MPa and the HAN-CMA shows ITSM results of 1120MPa.

AC 10 HAN-CMA Results

The independent laboratory results show that the AC 10 HAN-CMA has an ITSM of 750MPa at 3 days curing, this is half of the minimum target of 1500MPa. The LJMU laboratory shows ITSM results of 1750MPa at 3 days curing, showing 1000MPa difference in stiffness.

- 7 days of curing shows that the test results from the independent laboratory exceed the LJMU results. At 7 days curing, the LJMU laboratory reports ITSM of 2000MPa, whilst the independent laboratory report ITSM results of 3000MPa.
- At 14 days of curing, the independent laboratory report ITSM results of 3725MPa. The LJMU laboratory reports ITSM results of 2700MPa.
- At 28 days of curing, the independent laboratory reports ITSM results of 4120MPa. The LJMU laboratory reports ITSM results of 3750MPa.

AC 20 HAN-CMA Results

At 3 days curing the ITSM results reported from the independent laboratory, XAIS-PTS, are 800MPa this is 3 times below the minimum target of 2500MPa set for the AC 20 samples. This reported ITSM result is also almost 2000MPa below the reported result of the LJMU laboratory, raising concerns for the materials early curing strength.

- At 7 days of curing the independent laboratory reports and ITSM result of 4250MPa, a difference of nearly 3500MPa in 4 days. As mentioned, the 3 day samples ITSM results are from a secondary batch which may explain the contrast in stiffness between 3 days and 7 days curing. At 7 days the LJMU laboratory ITSM reports results of 3250MPa.
- At 14 days of curing the independent laboratory reports ITSM of 5075MPa. The LJMU laboratory reported ITSM of 4250MPa.
- At 28 days curing both the independent laboratory and the LJMU laboratory both show ITSM results reaching 5500MPa for the AC 20 HAN-CMA samples.

AC 20 HAN-CMA with 20% RAP Results

HAN-CMA results with 20% RAP has a reduced stiffness at 3 days curing according to the independent laboratory results. The reported results show that the AC 20 HAN-CMA with 20% RAP has ITSM of 1300MPa at the independent laboratory and 2800MPa at LJMU laboratory. The independent laboratory results are lower than the target of 2500MPa for the AC 20 materials.

- At 7 days curing, the results from the LJMU laboratory are still greater than the reported ITSM results of the independent laboratory. The LJMU laboratory reports ITSM results of 3330MPa, and the independent laboratory reporting results of 2650MPa.
- At 14 days curing, the independent laboratory ITSM results surpass the results of the LJMU laboratory. The results show, 4450MPa from the independent laboratory and 4075MPa from the LJMU laboratory.
- At 28 days curing, the independent laboratory reported an ITSM result 6600MPa which is a significant increase in stiffness compared to the results from the LJMU laboratory reporting 4900 MPA.

The ITSM results from the independent laboratory, XAIS-PTS, are concerning as the stiffness of the AC 20 HAN-CMA samples at 3 days curing is extremely low, all of the samples have results below the minimum ITSM target. As mentioned, the samples for 3 day testing were sent separately and at approximately 3 months after the samples used for the results between 7 to 28 days. The correlation between the 3 days curing and the 7 to 28 days curing samples is poor, suggesting that the 3 days samples are underperforming. This could be due to damage during the transportation of the samples to the independent laboratory as the LJMU team experienced with the slabs for the wheel track test. This also could be an error during the production of the samples from the LJMU team. Due to financial constraints the samples for 3 days could not be sent to the independent laboratory for re-testing.

Apart from the day 3 samples, all of the independent laboratory test results showed higher results than the LJMU laboratory test results, assuring the quality of the test results from the LJMU laboratory. The independent laboratory reported higher ITSM values than those obtained in the LJMU laboratory. This indicates that the LJMU results represent a conservative estimate of stiffness and can therefore be considered suitable for use in the analysis.

LJMU Low Heat Asphalt (LHA) Results

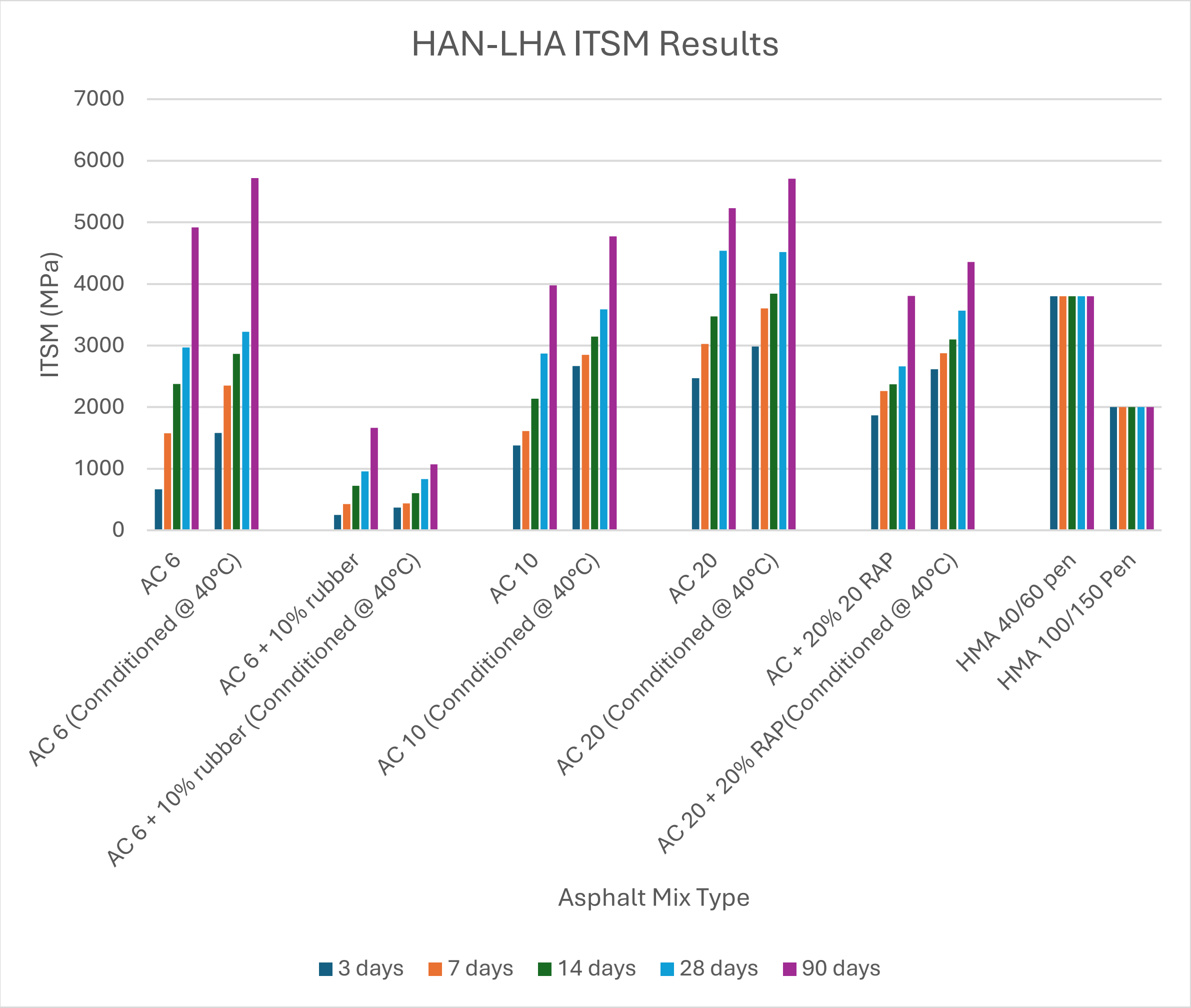

Figure 11. HAN-LHA ITSM Results

The HAN- LHA samples are made up from the same materials as the HAN-CMA, the difference being that the LHA mixtures were heated to 60°C to enhance the durability of the asphalt material by reducing the viscosity of the modified emulsion for better coating of the aggregate. The figure above shows the ITSM results for the HAN- LHA unconditioned and conditioned samples. The ITSM results labelled 'conditioned' are conditioned for 24 hours after de-moulding at 40°C to simulate intermediate field curing. The HAN- LHA ITSM results are shown over 90 day curing period.

AC 6 HAN-LHA Results

The LJMU results are seen on the figure above. The results from the figure above show,

- 3 days curing: The AC 6 HAN- LHA recorded ITSM values of 665 MPa for the unconditioned samples and 1580 MPa for the conditioned samples, both exceeding the target minimum stiffness of 500 MPa for AC 6 mixtures. However, the LHA samples showed slightly lower stiffness than the CMA samples at this stage.
- 7 days curing: The AC 6 HAN-LHA showed a significant increase in stiffness, with ITSM values of 1575 MPa for the unconditioned samples and 2350 MPa for the conditioned samples. At this stage, the unconditioned HAN-LHA samples demonstrated higher stiffness than the HAN-CMA, while the conditioned HAN-CMA samples remained stiffer than the conditioned HAN-LHA samples. The HAN-LHA samples also showed higher stiffness than the HMA samples, indicating good potential for use as a road surface material.
- 14 days curing: The AC 6 HAN-LHA recorded ITSM values of 2375 MPa for the unconditioned samples and 2875 MPa for the conditioned samples. The unconditioned HAN-LHA samples were approximately 500 MPa stiffer than the CMA unconditioned samples, while the conditioned HAN-CMA samples remained around 700 MPa stiffer than the conditioned HAN-LHA samples.
- 28 days curing: The AC 6 HAN-LHA continued to gain stiffness, with ITSM values of approximately 2975 MPa for the unconditioned samples and 3225 MPa for the conditioned samples. The unconditioned HAN-LHA samples showed greater stiffness than the HAN-CMA samples by around 400 MPa, although the conditioned HAN-CMA samples continued to exhibit higher stiffness than the conditioned HAN-LHA samples
- 90 days curing: The AC 6 HAN-LHA achieved ITSM values of 4920 MPa for the unconditioned samples and 5720 MPa for the conditioned samples. At this stage, the unconditioned HAN-LHA and HAN-CMA samples showed similar stiffness values of approximately 5000 MPa, indicating a high level of stiffness after extended curing.

Overall, the results demonstrate that the AC 6 HAN-LHA mixture develops stiffness steadily with curing time, exceeding the minimum stiffness requirement from the early curing stage and continuing to gain strength over time. While the HAN-CMA mixtures generally exhibit higher stiffness in the conditioned state, the HAN-LHA mixtures show comparable or higher stiffness in the unconditioned state after extended curing, suggesting that the LHA mixture performs well as a potential road surface material.

AC 6 HAN-LHA with 10% Rubber LHA Results

- 3 days curing: The HANB-LHA samples showed low ITSM values of 250 MPa for the unconditioned samples and 370 MPa for the conditioned samples, both below the target stiffness of 500 MPa. At this stage, the HAN- LHA results were slightly lower than those recorded for the HAN-CMA samples.

- 7 days curing: The HAN-LHA samples remained below the 500 MPa target, with ITSM values of 424 MPa for the unconditioned samples and 440 MPa for the conditioned samples. The stiffness values were still lower than those observed for the HAN-CMA mixtures at the same curing stage.
- 14 days curing: The unconditioned samples showed higher stiffness than the conditioned samples, suggesting that heating may have a negative effect on the rubber crumb, potentially limiting strength development. The unconditioned samples recorded an ITSM value of 725 MPa, while the conditioned samples showed 600 MPa. At this stage, the HAN-CMA AC 6 with 10% rubber exceeded the 500 MPa target stiffness.
- 28 days curing: The samples continued to gain stiffness, with ITSM values of 960 MPa for the unconditioned samples and 830 MPa for the conditioned samples. However, the HAN-CMA mixtures still demonstrated higher stiffness values at this stage.
- 90 days curing: The unconditioned samples reached ITSM values of approximately 1600 MPa, similar to the unconditioned HAN-CMA samples and comparable to the stiffness typically observed in HMA mixtures. The conditioned HAN-LHA samples recorded a lower stiffness of 1070 MPa.

The AC 6 HAN- LHA mixture containing 10% rubber crumb (LHA) exhibited lower overall stiffness compared with the HAN-CMA mixture, suggesting that increased heating during conditioning did not significantly enhance the curing or stiffness development of the material. The reduced SMR index observed for the mix with 10% rubber is likely associated with the swelling behaviour of the rubber crumb within the asphalt binder. During this swelling process, the rubber particles absorb lighter fractions of the binder, which can alter the internal structure of the mixture. Previous research indicates that prolonged swelling of rubber in asphalt can lead to rubber ageing, the formation of polar groups, and an increase in the glass transition temperature of the rubber. As a result, the rubber may begin to behave more like a brittle glassy material rather than an elastic rubber, which can limit strength development and reduce the stiffness gain of the mixture over time (Wulandari, P et al. 2019).

AC 10 HAN-LHA Results

The ITSM minimum target for the AC 10 samples is 1500MPa.

- 3 days curing: The HAN-LHA recorded an ITSM value of 1375 MPa, which is below the 1500 MPa target. The conditioned samples showed significantly higher stiffness, with results of approximately 2665 MPa. The AC 10 HAN-CMA mixture produced higher ITSM values for the unconditioned samples compared to the LHA, while the conditioned samples for both mixtures showed similar stiffness values of around 2600 MPa.
- 7 days curing: The AC 10 HAN-LHA exceeded the target stiffness with an ITSM value of 1609 MPa, while the conditioned samples recorded an average stiffness of approximately 2850 MPa. The AC 10 HAN-CMA mixture again demonstrated

higher stiffness, with unconditioned samples exceeding 2000 MPa and conditioned samples exceeding 3400 MPa.
- 14 days curing: The stiffness of the HAN-LHA samples continued to increase, reaching 2135 MPa for the unconditioned samples and 3150 MPa for the conditioned samples.
- 28 days curing: Stiffness continued to increase, with ITSM values of 2870 MPa for the unconditioned samples and 3585 MPa for the conditioned samples.
- 90 days curing: The AC 10 HAN-LHA reached an ITSM value of 3980 MPa for the unconditioned samples and 4775 MPa for the conditioned samples. The HAN-CMA samples consistently demonstrated higher stiffness values throughout the curing period.

Overall, the results indicate that stiffness increases significantly with curing time, particularly for the HAN-LHA mixture, which gradually surpasses the target stiffness after 7 days and continues to develop strength over time. However, the HAN-CMA mixture consistently demonstrated higher ITSM values throughout the curing period, suggesting greater early-age stiffness compared with the HAN-LHA mixture.

AC 20 HAN-LHA Results

The ITSM target for all the AC 20 samples remains at 2500MPa.

- 3 days curing: The AC 20 HAN-LHA recorded ITSM values of 2470 MPa for the unconditioned samples and 2985 MPa for the conditioned samples. The unconditioned samples narrowly missed the target ITSM value of 2500 MPa. At this stage, the AC 20 HAN-CMA showed higher stiffness, with results exceeding 2750 MPa for the unconditioned samples and approximately 3750 MPa for the conditioned samples.
- 7 days curing: The AC 20 HAN-LHA samples showed increased stiffness, with ITSM values of 3025 MPa for the unconditioned samples and 3600 MPa for the conditioned samples. The AC 20 HAN-CMA continued to demonstrate higher stiffness, with results of 3250 MPa for the unconditioned samples and 4650 MPa for the conditioned samples.
- 14 days curing: The stiffness of the HAN-LHA samples further increased to 3475 MPa for the unconditioned samples and 3840 MPa for the conditioned samples. The CMA samples continued to show greater stiffness, recording 4260 MPa for the unconditioned samples and 5130 MPa for the conditioned samples.
- 28 days curing: At this stage, the HANB-LHA unconditioned samples unexpectedly showed slightly higher stiffness than the conditioned samples, with ITSM values of 4535 MPa and 4520 MPa, respectively. However, the HAN-CMA mixtures still exhibited higher stiffness overall.
- 90 days curing: The AC 20 HAN-LHA reached ITSM values of 5230 MPa for the unconditioned samples and 5700 MPa for the conditioned samples. The AC 20 HAN-LHA continued to demonstrate significantly higher stiffness, with results of 7600 MPa for the unconditioned samples and 9150 MPa for the conditioned samples.

Overall, the results show that stiffness increases progressively with curing time for both mixtures, with the AC 20 HAN-LHA gradually surpassing the target stiffness requirement after the early curing stage. However, the HAN-CMA mixtures consistently exhibited higher stiffness values throughout the curing period, indicating stronger early-age and long-term stiffness performance compared with the HAN-LHA mixtures.

AC 20 HAN-LHA + 20% RAP Results

- 3 days curing: The AC 20 HAN-LHA + 20% RAP recorded an ITSM value of 1870 MPa for the unconditioned samples, which is below the target stiffness of 2500 MPa. The conditioned samples showed increased stiffness due to curing at 40 °C, with ITSM results of approximately 2750 MPa for the unconditioned samples and 2900 MPa for the conditioned samples.
- 7 days curing: The LHA samples continued to show relatively low stiffness, with unconditioned samples recording 2260 MPa, still below the target value. The conditioned samples showed improved stiffness with an ITSM of 2890 MPa. At this stage, the HAN-CMA samples demonstrated higher stiffness values of 3330 MPa for the unconditioned samples and 3450 MPa for the conditioned samples.
- 14 days curing: The HAN-LHA samples showed limited strength gain, with the unconditioned samples reaching 2370 MPa, remaining below the 2500 MPa target. The conditioned samples increased slightly to 3100 MPa, representing only a modest increase compared with the 7 day results.
- 28 days curing: The unconditioned HAN-LHA samples surpassed the target stiffness, recording an ITSM value of 2665 MPa, while the conditioned samples reached 3570 MPa. The HAN-CMA mixtures continued to show higher stiffness, with results of 4900 MPa for the unconditioned samples and 4400 MPa for the conditioned samples.
- 90 days curing: The AC 20 HAN-LHA + 20% RAP reached ITSM values of 3800 MPa for the unconditioned samples and 4350 MPa for the conditioned samples. However, the LHA mixtures did not reach the same stiffness levels as the CMA mixtures over the 90-day curing period. The AC 20 HAN LHA + 20% RAP continued to demonstrate higher stiffness, with values of 6900 MPa for the unconditioned samples and 6200 MPa for the conditioned samples.

Overall, the results show that stiffness increases with curing time, although the HAN-LHA mixtures with 20% RAP develop stiffness more slowly and only exceed the target value after extended curing. In comparison, the CMA mixtures consistently demonstrate higher stiffness throughout the curing period, indicating stronger early-age and long-term stiffness performance.

Wheel Track Test

The wheel tracking test is used to assess the permanent deformation resistance of asphalt materials. Rutting occurs slowly under heavy traffic loads over a long period of time and is a main cause of failure in flexible pavement (Dulaimi *et al.* 2020). This test is done by repeating a series of passes by a loaded rubber wheel that creates a rut in the sample, the depth of the rut gives us an indication to the rutting performance and durability of the material.

For this test an asphalt slab was required with dimensions, 400mm x 305mm x 50mm. The sample was made in a steel frame and compacted in the roller compactor here at LJMU laboratory as seen in figure following BS EN 12697-33 (CEN, 2003b). The testing was conducted at 45°C to assess rutting at moderate to heavily trafficked recommended in the BS EN 12697-22 (CEN, 2003a). The test procedures also followed BS EN 12697-22 using a 'HYCZ-5' wheel tacking machine seen in figure (CEN, 2003a). The equipment uses a rubber tyre (50mm width) which runs at 42 passes a minute with a load stress of 0.7MPa in contact with the slab until the slab reaches 10,000 cycles or 20mm rutting depth. The samples are cured at 45°C 4 hours before the testing takes place. The table below shows the test conditions.

Table 3. Wheel Track Test Conditions

Parameter	Range
Outside diameter of the tyre (mm)	200 – 205
Tyre width (mm)	50±5
Travel distance (mm)	230±10
Travel speed (time/min)	42±1
Contact Pressure (MPa)	0.7±0.05
Poisson's ratio	0.35
No. of conditioning cycles	5
No of test cycles	10,000
Test temperature (°C)	45
Compaction	Roller compactor
Temperature conditioning	4 hours before testing

HAN-CMA Results

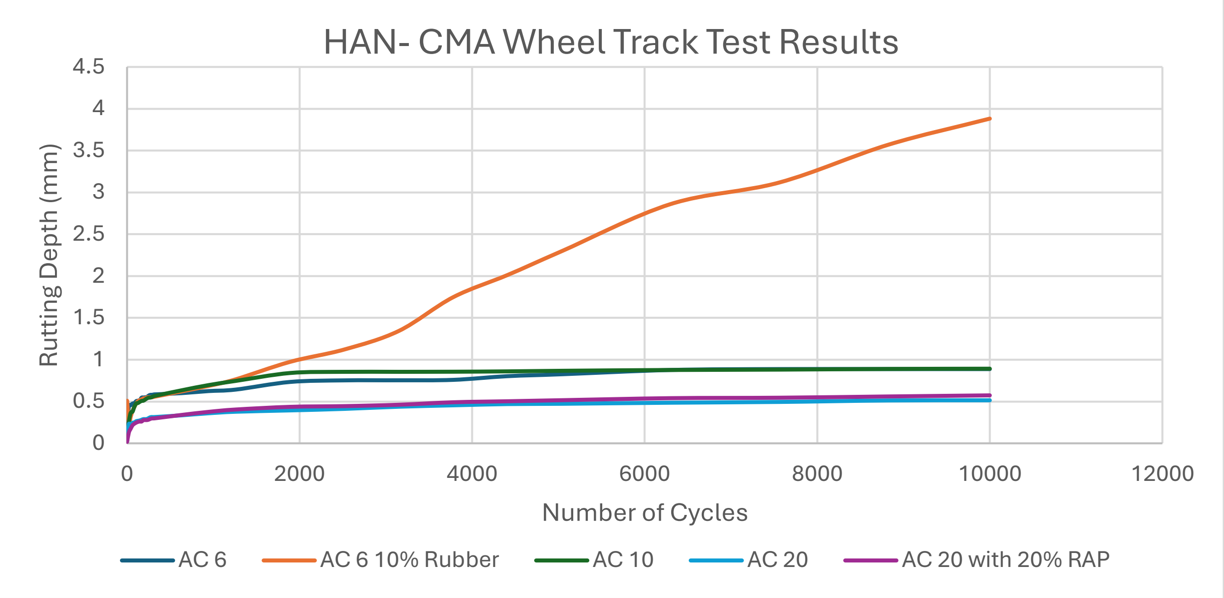

Figure 12. LJMU CMA Wheel Track Results

Figure 12. shows the rutting depth from the results of the wheel track test for the HAN-CMA samples.

AC 6 HAN-CMA Results

The target set for the rutting depth is 4mm after 10,000 cycles.

- The AC 6 HAN-CMA has a maximum rut depth less than 1mm after 10,000 cycles. This shows high resistance to rutting deformation.
- The AC 6 HAN-CMA with 10 % of rubber HAN-CMA has a maximum rut depth value of 3.85mm at 10,000 cycles. Less than the 4 mm recommended values for roads with “moderate to heavily stressed sites” (BS EN 13108, 2010).
- Continued work needs to de done to investigate the optimisation of the rubber crumb content in the AC 6 HAN-CMA + 10% Rubber CMA as there is approximately 3mm difference in maximum rutting depth with the AC 6 HAN-CMA without rubber.

AC 10 HAN-CMA Results

- The AC 10 HAN-CMA has a maximum value at 1000 cycles of 0.9mm < 4 mm recommended values for roads with “moderate to heavily stressed sites” (BS EN 13108, 2010).
- AC 10 HMA has a maximum rutting depth of 3.3mm at 10,000 cycles (Al-Busaltan, 2012). Showing the AC 10 HAN-CMA has excellent rutting resistance.

AC 20 HAN-CMA Results

- The AC 20 HAN-CMA has a maximum rutting depth of 0.515mm at 10,000 cycles, which is significantly lower than the 4mm recommended values for roads values for roads with “moderate to heavily stressed sites” (BS EN 13108, 2010).

- The AC 20 HAN-CMA with 20% RAP CMA has a maximum rut depth of 0.565 mm at 10000 cycles. Which is slightly higher than the results of LJMU AC 20 CMA without any RAP.
- AC 20 HMA without RAP maximum rutting depth at 10000 numbers of load cycles was 2.65 mm. Showing that AC 20 HAN-CMA types have greater rut resistance than the HMA (Al-Busaltan, 2012).

HAN-CMA Wheel Track Results - XAIS-PTS Independent Laboratory Results

XAIS-PTS Results –AC 6 + 10% Rubber, AC 10-+ 10% Rubber, AC 20

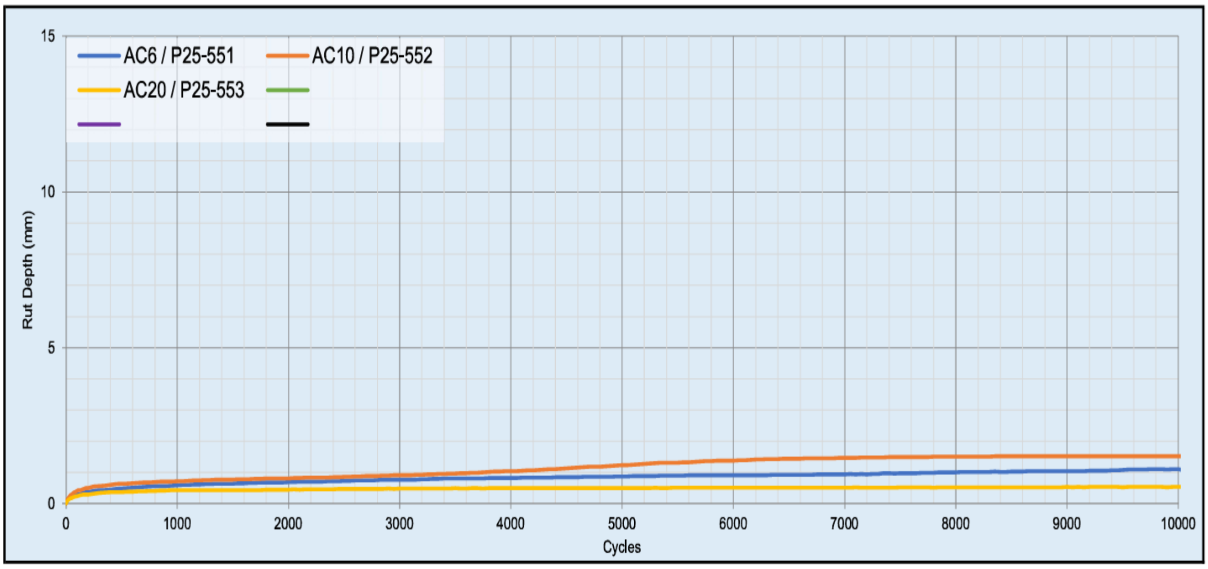

Figure 13. LJMU CMA Wheel Track Test Results from XAIS-PTS

XAIS-PTS Results , AC 6-HAN-CMA, AC 10-HAN-CMA, AC 20-HAN -CMA + 20% RAP

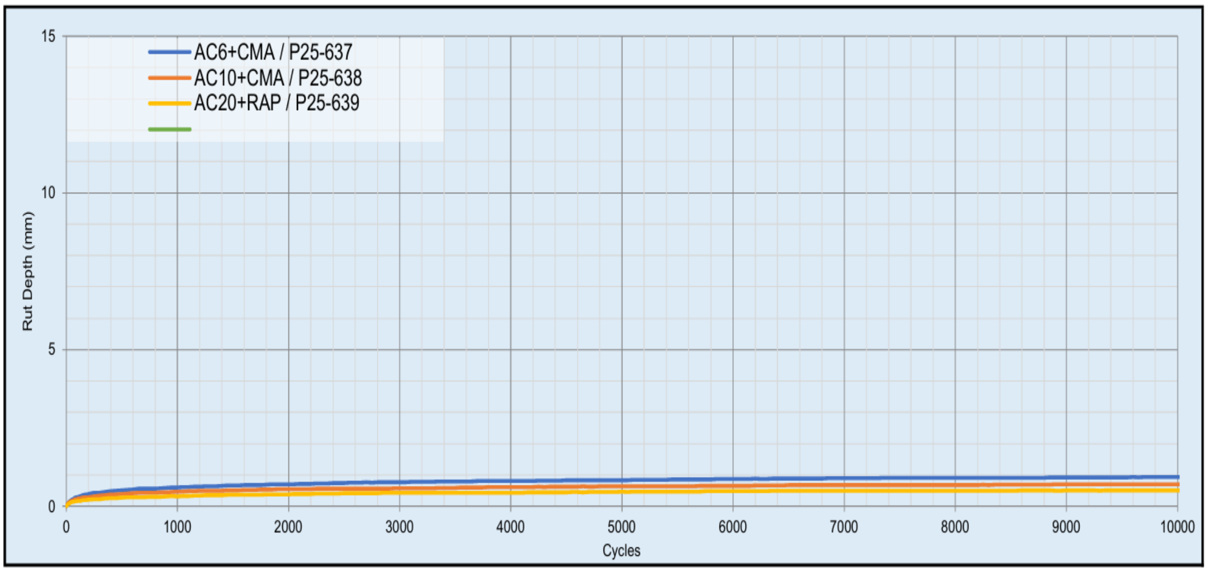

Figure 14. LJMU CMA Wheel Track Test Results from XAIS-PTS

The two figures above show the wheel track test results from the independent laboratory. The reason for two figures being shown, unfortunately on our first visit to XAIS-PTS laboratory some of the samples were damaged during transit and were unable to be tested. The same testing procedures were applied at the independent laboratory as the LJMU Laboratory. The testing was conducted at 45°C to assess rutting at moderate to heavily trafficked recommended in the BS EN 12697-22 (CEN, 2003a).

Also note, there are results for AC 10 HAN-CMA with 10% rubber in this section. After reviewing the materials performance, the AC 10 HAN-CMA with 10% rubber was removed from the project.

AC 6 HAN-CMA Independent laboratory Results

- The AC 6 HAN-CMA shows a maximum rut depth of 1mm at the independent laboratory. The maximum rut depth of the AC 6 HAN-CMA recorded from the LJMU laboratory was 0.9mm, showing a deviation of 0.1mm between the two testing facilities.
- The AC 6 HAN-CMA with 10 % of rubber has a maximum rut depth of 2.2mm from the independent laboratory. Showing a much greater resistance to rutting that the maximum rut depth measured at the LJMU laboratory by 1.65mm.
- Both Results still satisfy our maximum target of 4mm rut depth after 10,000 cycles.

AC 10 HAN-CMA Independent laboratory Results

- The AC 10 HAN-CMA shows a maximum rut depth of 0.8 mm at the independent laboratory. The maximum rut depth of the LJMU AC 6 recorded from the LJMU laboratory was 0.9mm, again, showing a deviation of 0.1mm between the two testing facilities.
- Interestingly, the independent lab shows greater rut resistance than the LJMU testing facility both results comply with the target of a maximum rut depth of 4mm.

AC 20 – HAN-CMA Independent laboratory Results

- The AC 20 HAN-CMA has a maximum rutting depth of 0.6mm from the independent laboratory and 0.5.15 at the LJMU laboratory. There is a difference of 0.085mm between the two facilities, showing accuracy in the durability of the AC 20 HAN-CMA material.
- The AC 20 HAN-CMA with 20% RAP CMA has a maximum rut depth of 0.5mm at the independent laboratory and 0.565 mm at LJMU laboratory at 10000 cycles.

The results show that all of the HAN-CMA materials are durable, all showing rutting depth below the 4mm recommended values for roads values for roads with “moderate to heavily stressed sites” (BS EN 13108, 2010). Excluding the AC 6 with rubber, all of the testing had a deviation of 0.1mm or below between both testing facilities, showing accuracy in testing and quality assurance in the HAN-CMA materials.

HAN- LHA Results

The figure 15 shows the results for the HAN-LHA samples. The decision to develop the HAN-LHA was to improve the durability of the material compared to the HAN- CMA mixes. Therefore, increased resilient performance to weathering and traffic loading is expected with the HAN-LHA samples.

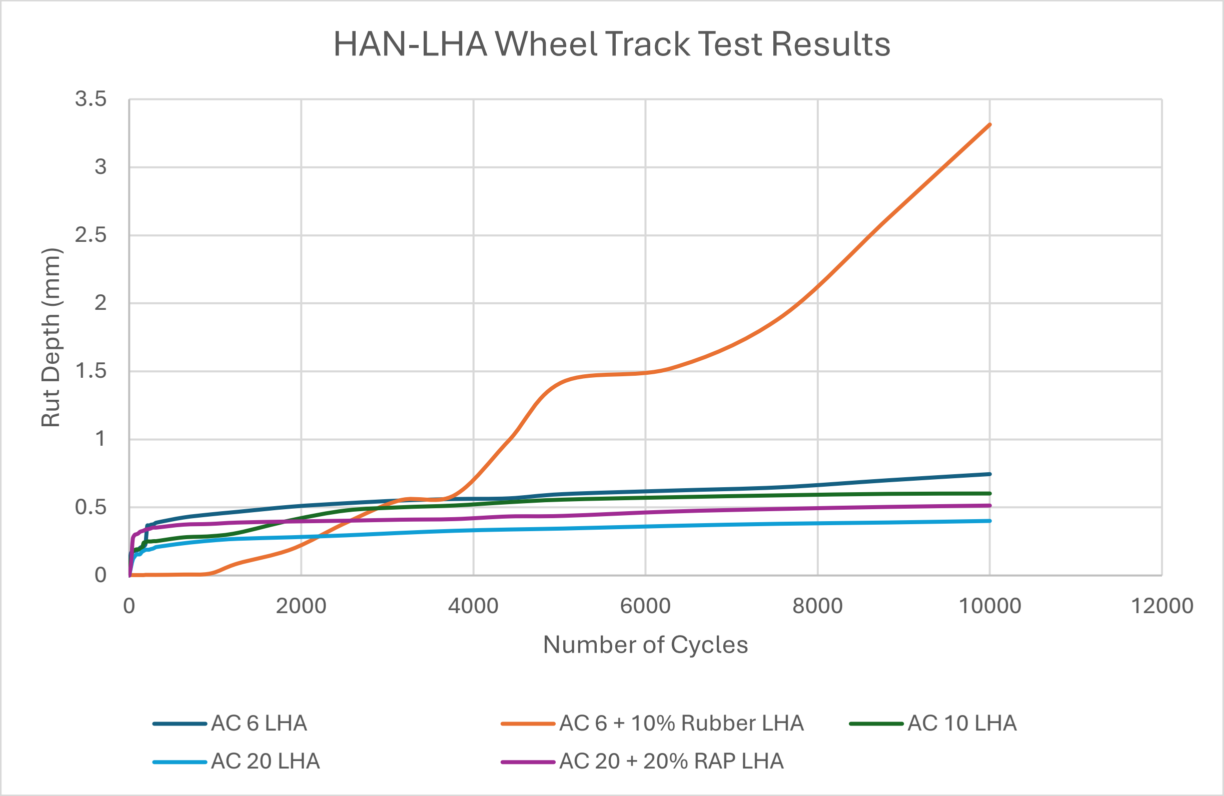

Figure 15. LHA-LHA Wheel Track Test Result

AC 6 HAN-LHA Independent laboratory Results

- The AC 6 HAN-LHA shows a maximum rut depth of 0.75mm after 10,000 cycles The maximum rut depth of the AC 6 was 0.9mm, showing an increased rutting resistance in the HAN-LHA.
- The AC 6 HAN-LHA with 10 % of rubber LHA has a maximum rut depth of 3.3mm, and the HAN-CMA has a maximum rut depth of 3.85mm, showing an increased rutting resistance of 0.55mm.
- Both Results still satisfy our maximum target of 4mm rut depth after 10,000 cycles, but the HAN-LHA sees improvement in rutting resistance compared to the HAN-CMA results showing in the figure in the report sections above.

AC 10 HAN-LHA Independent laboratory Results

- The AC 10 HAN-LHA has a maximum rutting depth of 0.6mm, whilst the AC 10 HAN-CMA10 has a maximum rutting depth of 0.9mm at 10,000 cycles.

- AC 10 HAN-LHA has a maximum rutting depth of 3.3mm at 10,000 cycles. Showing that the AC10 HAN-CMA and HAN-LHA have superior rutting resistance to the HMA.

AC 20 HAN-LHA Results

- The AC 20 HAN-LHA shows a maximum rutting depth of 0.4mm and the AC 20 HAN-CMA has a maximum rutting depth of 0.515mm at 10,000 cycles. Both of which are significantly lower than the 4mm recommended values for roads values for roads with “moderate to heavily stressed sites” (BS EN 13108, 2010).
- The AC 20 HAN-LHA with 20% RAP has a maximum ruth depth of 0.515mm and the 20% RAP HAN-CMA has a maximum rut depth of 0.565 mm at 10000 cycles. The AC20 HAN-CMA samples with RAP show slightly higher deformation under rutting test.
- AC 20 HMA without RAP maximum rutting depth at 10000 numbers of load cycles was 2.65 mm. Showing that both AC 20 HAN-CMA and HAN-LHA types have greater rut resistance than the HMA (Dulaimi, 2016). All of which are beneath the maximum 4mm recommended values for roads values for roads with “moderate to heavily stressed sites” (BS EN 13108, 2010).

Four-point bending Test

Fatigue resistance is determined from the four-point bending test. Fatigue cracking is the result of repeated loading on the asphalt due to traffic loading with a maximum value which is less than the maximum tensile strength (read, 1996). Fatigue cracking is the most common type of asphalt damage (N. Sudarsanan and Y. Kim, 2022). In order to make these samples, 400mm x 305mm x 50mm slabs were made following the same process as for the fatigue test, compacted in the roller compactor following BS EN 12697-33 (CEN, 2003b). Once the samples had cured, they were cut down to 50mm strips (width) leaving 400mm x 50mm x 50mm samples.

The four-point bending test was done following in accordance with BS EN 12697-24 (CEN, 2012). The fatigue life is determined by the number of pulses that result in 50% reduction of stiffness from the original value recorded. The fatigue lives of the samples were determined at 100,150 and 2000 micro strain as, Brown and Needham, suggest that strain level in pavements are likely to be lower than 200 micro strains. The samples with a dimension of 400mm x 50mm x 50mm are placed into the testing equipment, where the two outer clamps keep the sample fixed in place and the internal clamps provide a load in the vertical axis, creating a constant strain in the sample. The test was carried out at 20°C with a frequency of 10Hz, under sinusoidal waveform in the controlled strain mode. The test conditions are seen in the table below.

Table 4. 4 Point Bending Test Conditions

Parameter	Range
Control method	Constant strain
Test Temperature (°C)	20±1
Sample dimension (mm)	400x50x50
Frequency (Hz)	10
Micro strain	100 – 150
Initial Stiffness end value (50%)	50

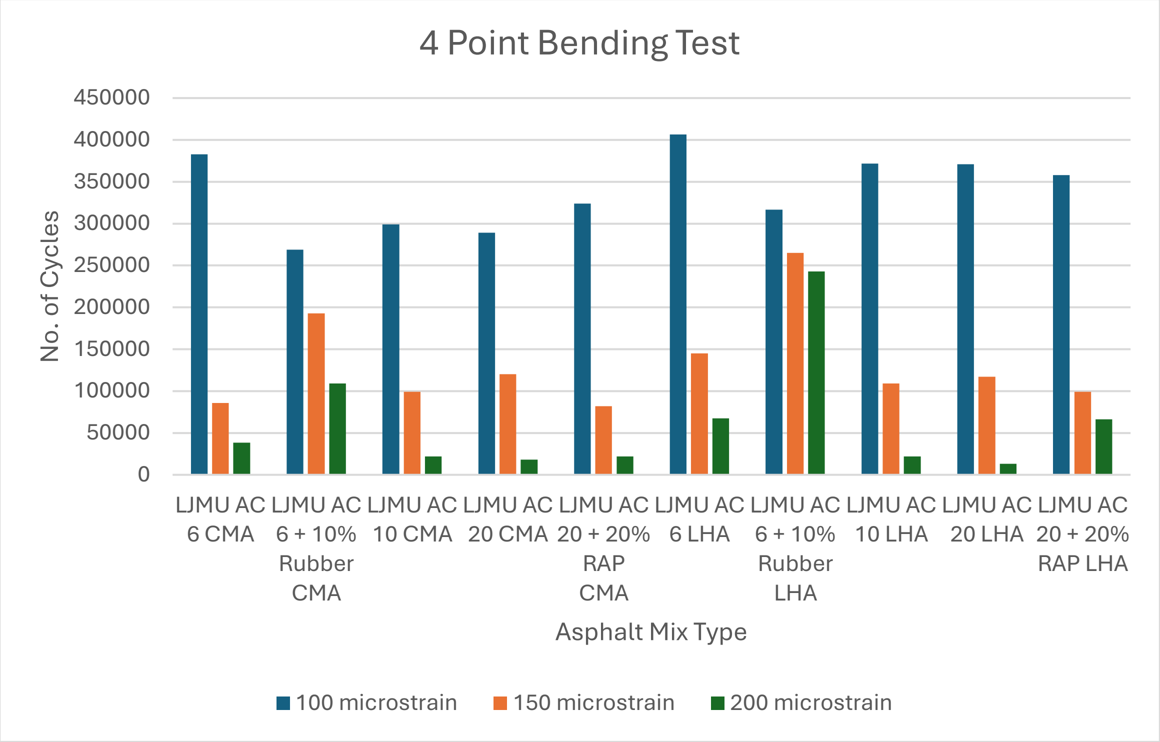

Figure 16. 4 Point Bending Test Results

The figure 16 above shows the results from the 4-point bending test, this test was done in accordance with BS EN 12697-24. The figures show the results from the LJMU laboratory for 100, 150 and 200 micro strains.

- AC 6 HAN-CMA achieved approximately 380,000 cycles at 100 micro strain, 85,000 cycles at 150 micro strain, and 38,500 cycles at 200 micro strain.
- AC 6 + 10% rubber HAN-CMA recorded 270,000 cycles at 100 micro strain, 193,000 cycles at 150 micro strain, and 109,000 cycles at 200 micro strain.
- AC 10 HAN-CMA achieved 300,000 cycles at 100 micro strain, 100,000 cycles at 150 micro strain, and 22,000 cycles at 200 micro strain.
- AC 20 HAN-CMA showed 290,000 cycles at 100 micro strain, 120,000 cycles at 150 micro strain, and 18,000 cycles at 200 micro strain.

- AC 20 + 20% RAP HAN-CMA achieved 324,000 cycles at 100 micro strain, 82,000 cycles at 150 micro strain, and 22,000 cycles at 200 micro strain.
- AC 6 HAN-LHA demonstrated improved fatigue resistance compared to AC 6 CMA, with 407,000 cycles at 100 micro strain, 150,000 cycles at 150 micro strain, and 67,000 cycles at 200 micro strain.
- AC 6 + 10% rubber HAN-LHA showed further improvement, particularly at higher strain levels, with 317,000 cycles at 100 micro strain, 265,000 cycles at 150 micro strain, and 243,000 cycles at 200 micro strain.
- AC 10 HAN-LHA achieved 372,000 cycles at 100 micro strain, 109,000 cycles at 150 micro strain, and 22,000 cycles at 200 micro strain.
- AC 20 HAN-LHA recorded 371,000 cycles at 100 micro strain, 117,000 cycles at 150 micro strain, and 13,000 cycles at 200 micro strain.
- AC 20 + 20% RAP (HAN-LHA) showed 358,000 cycles at 100 micro strain, 99,000 cycles at 150 micro strain, and 66,000 cycles at 200 micro strain.

Overall, the HAN-LHA demonstrate improved fatigue performance compared to their HAN-CMA counterparts, particularly at higher strain levels. The addition of rubber crumb significantly enhances fatigue resistance, especially at 150 and 200 micro strain. While RAP inclusion provides some benefit at lower strain levels, its performance is more variable at higher strains. Among all mixtures, AC 6 + 10% rubber produces the greatest overall fatigue resistance, particularly under higher strain conditions, proving its durability properties. This needs further investigation to optimise the rubber dust percentage in the mixtures.

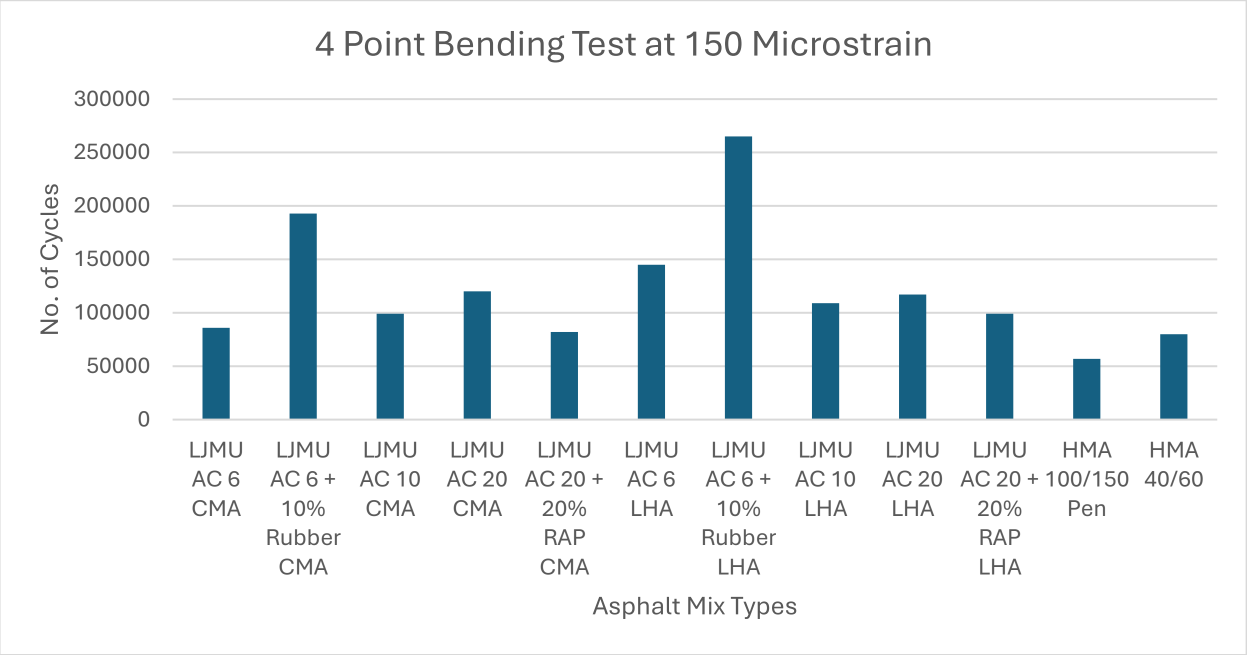

Figure 17. 4 Point Bending Test at 150 Micro strain

The figure 17 above shows the results for the 4-point bending test compared with HMA samples at 150 micro strain.

- AC 6 HAN-CMA achieved approximately 85,000 cycles.
- AC 6 + 10% rubber HAN-CMA showed significantly higher fatigue resistance, with around 193,000 cycles.
- AC 10 HAN-CMA recorded approximately 100,000 cycles.
- AC 20 HAN-CMA performed slightly better, with about 120,000 cycles.
- AC 20 + 20% RAP (CMA) showed reduced performance, with approximately 82,000 cycles.
- AC 6 HAN-LHA demonstrated improved fatigue resistance compared to its HAN-CMA counterpart, achieving around 145,000 cycles.
- AC 6 + 10% rubber HAN-LHA exhibited the highest fatigue resistance among all mixtures, with approximately 265,000 cycles.
- AC 10 HAN-LHA showed similar performance to its HAN-CMA equivalent, at around 108,000 cycles.
- AC 20 HAN-LHA recorded approximately 117,000 cycles, comparable to AC 20 HAN-CMA.
- AC 20 + 20% RAP (HAN-LHA) achieved around 99,000 cycles, showing improvement over the AC 20 + 20% RAP HAN-CMA mix.
- HMA 100/150 Pen showed the lowest fatigue performance, with approximately 55,000 cycles.
- HMA 40/60 performed better than 100/150 Pen, with around 80,000 cycles

At 150 micro strain, mixtures incorporating HAN-LHA outperform their HAN-CMA equivalents, particularly for AC 6 mixes. The addition of rubber provides a substantial improvement in fatigue resistance, with AC 6 HAN-LHA + 10% rubber showing the best overall performance. The inclusion of 20% RAP tends to reduce fatigue life in HAN-CMA mixes but performs slightly better as an HAN-LHA mixture. Conventional HMA mixtures exhibit the lowest fatigue resistance, indicating that the new asphalt mixtures provide greater resistance to fatigue cracking.

Water Sensitivity

The water sensitivity test is conducted in order to determine how the material behaves when it comes in contact with water. Moisture damage in asphalt mixtures can result in reduced stiffness due to the loss of adhesion and viscous bonding between the binder and aggregate within the material. This will therefore lead to an overall reduction in strength and durability of the asphalt.

The water sensitivity test was done in accordance with BS EN 12697-12 (CEN,2008). For this test two sample batches are produced following the Marshall Method. The first set of samples were the unconditioned (dry) set, which were demoulded after 24 hours of curing and then left for 7 days of curing in the lab at 20°C before the ITSM testing was conducted. The second set were the conditioned (wet) samples. These samples were demoulded after 24 hours and left to cure for a further 4 days at 20°C before undergoing the conditioning procedure. The first step, the samples were placed into a vacuum submerged in water at a pressure of 6.7kPa for 30 minutes at room temperature. The samples were then left for a further 30 minutes submerged gradually depressurising back to atmospheric pressure. This is done slowly to ensure that the samples aren't damaged due to expansion. The samples are then submerged in a water bath set at 40°C for 3 days before undergoing ITSM testing at 20°C. Once both sets had completed the ITSM testing, the results were analysed to determine the stiffness modulus ratio (SMR) of the wet to dry samples as a percentage.

SMR = (Wet ITSM / Control ITSM) × 100

HAN-CMA Results

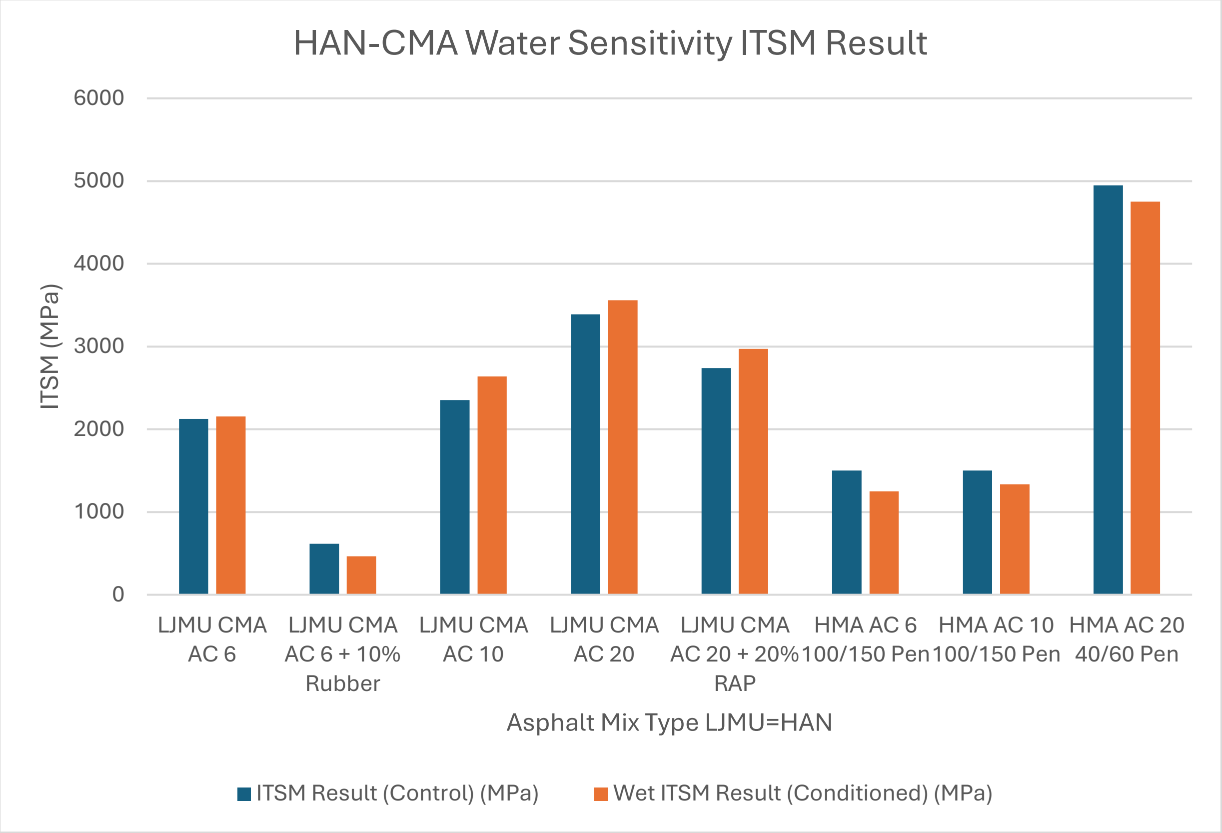

Figure 18. HAN-CMA Water Sensitivity Results

AC 6 HAN-CMA Results

The figure 18 above presents the ITSM results of the AC 6 HAN-CMA specimens, comparing those subjected to the required conditioning parameters for the water sensitivity test with those that were not conditioned. You can see that there is very little difference between the ITSM results, there is 1.5% gain in stiffness due to the conditioning parameters of the water sensitivity test. The HMA AC 6 ITSM result decrease under the conditioning parameters by 17.5%. For HAN-CMA, this is due to the increase in the hydration process within the AC 6 HAN-CMA under the conditioning parameters required for this test. This is a contrast to the reduction of cohesion and bonding that occurs when HMA AC6 samples subjected to the water sensitivity test conditions.

The AC 6 HAN-CMA with 10% rubber doesn't follow the same trend as the other HAN-CMA materials, the ITSM results after being subjected to the water sensitivity test conditions reduce compared to the unconditioned samples. The conditioned ITSM result as reduced by 24.5% compared to the unconditioned samples.

AC 10 HAN-CMA Results

It can be seen in figure 18, that the ITSM results of the new AC 10 HAN-CMA are greater than HMA AC10 (100/150pen). The ITSM results of the new AC 10 HAN-CMA increase by

12% after being subject to the conditioning parameters, whereas the HMA AC10 ITSM results reduce by 11%.

AC 20 HAN-CMA Results

ITSM results of both the new AC 20 HAN-CMA with and without RAP, show increased stiffness compared with HMA AC 20. The ITSM values of the new AC 20 HAN-CMA increase by 5% whilst the new AC 20 with 20% RAP HAN-CMA increase by 8% under the conditioning parameters. The HMA AC20 ITSM results reduce by 5% after being subject to the conditioning parameters.

This indicates that all new HAN-CMA materials, excluding the AC 6 with 10% rubber HAN-CMA, demonstrated an increase in stiffness when subjected to the water sensitivity test conditions, suggesting that the materials would continue to perform adequately under high rainfall or flooding conditions.

LJMU LHA Results

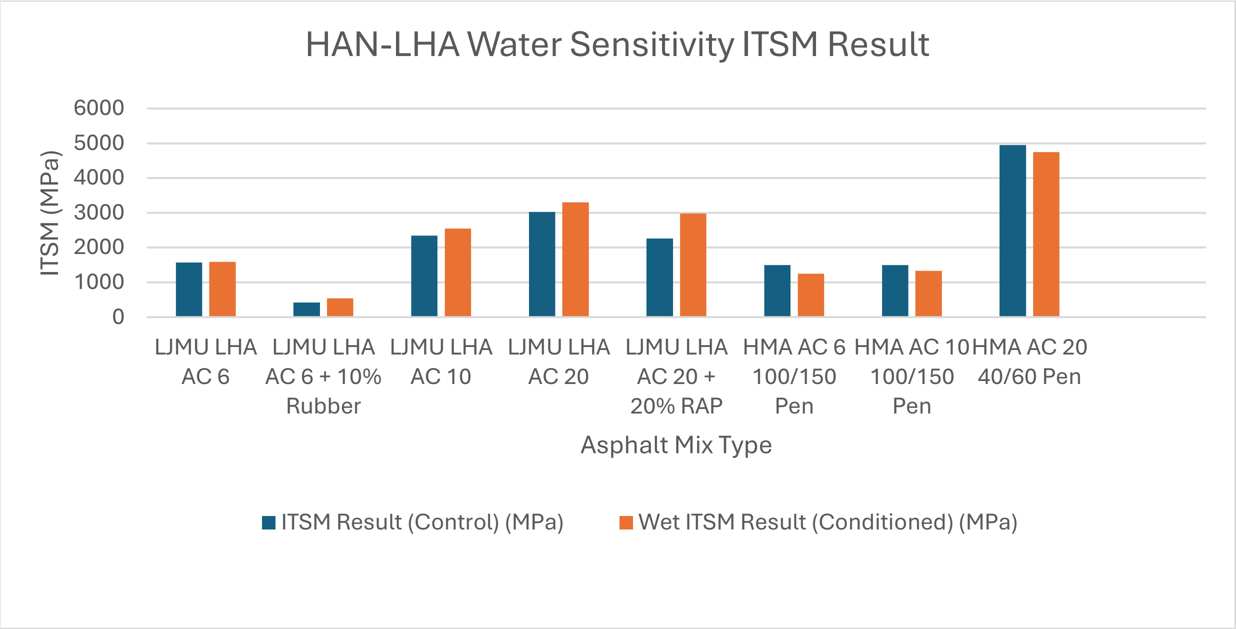

Figure 19. HAN-LHA Water Sensitivity ITSM Results

The figure 19 above presents the ITSM results of all the HAN-LHA samples, comparing those subjected to the required conditioning parameters for the water sensitivity test with those that were not conditioned. The SMR of the HAN- LHA materials and the HMA materials are similar, with the main difference showing an increased ITSM for HAN-LHA and a reduction in stiffness for the HMA samples respectively under water sensitivity test.

HAN-AC6 LHA

The new AC 6 LHA shows lower ITSM values compared to theAC6 HAN - CMA. The new HAN-LHA shows ITSM results of approximately 1600MPa, whilst the AC 6 HAN-CMA shows results of approximately 2100MPa. Although there is a reduced stiffness in the HAN-LHA compared with the HAN-CMA mixtures, the SMR remains similar. The HAN-CMA results showed an increase of stiffness of 1.5% after conditioning, the HAN-LHA shows a stiffness gain of 1% after conditioning.

The new AC 6 with rubber HAN-CMA conditioned ITSM result as reduced by 24.5% compared to the unconditioned sample. This time, the AC 6 with rubber HAN-LHA follows the same trend as the other samples and increases its stiffness by 26% when subjected to water sensitivity conditioning.

The HMA results stay the same as the results from HAN-CMA with HMA AC 6 ITSM result reducing by 17.5% after undergoing water sensitivity testing.

LJMU AC 10 LHA Results

It can be seen in figure 19, that the ITSM results of the AC 10 HAN - LHA are similar to the AC 10 HAN-CMA. The LHA samples show unconditioned ITSM results of approximately 2350MPa and conditioned results of 2550MPa, increasing by 8.5%. The HAN-CMA samples show a slightly larger stiffness gain of 12% after water sensitivity conditioning.

AC 20 HAN-LHA Results

The ITSM results of the new AC 20 HAN-LHA samples showed greater stiffness gain compared to the AC 20 HAN-CMA. The AC 20 HAN-LHA showed an unconditioned ITSM result of 3025MPa and a conditioned ITSM result of 3300MPa, increasing by 9%. The AC 20 HAN-CMA had a higher overall ITSM result but a reduced stiffness gain of 5% when conditioned.

The AC 20 with 20% RAP showed an unconditioned ITSM result of approximately 2250MPa and a conditioned ITSM result of 2975MPa, increasing by 31%. The AC 20 HAN- LHA with 20% rubber HAN-CMA had a higher unconditioned ITSM result with a stiffness gain of approximately 8.5% when subjected to the water sensitivity conditioning parameters.

Ageing

The ageing test is conducted by long term oven ageing which simulates the ageing of the asphalt mixture during its ‘use’ phase in real world applications. This test follows the recommendation by the Strategy Highway Research Program (SHRP) A003A where samples are cured for 5 days in an oven at 85°C to simulate 10 years of ageing. Kliewer et al. (1995) recommends that compacted asphalt samples which are stored in an oven for 2 days at 85°C simulate 5 years of age hardening, 5 days at 85°C simulates 10 years of age hardening. This test simulates the long-term ageing which will give an indication to the durability of the material.

Once again, for this testing two sets of samples were made following the Marshall method. The first set of samples were the unconditioned set which were demoulded 24hrs after production and left to cure for 5 days at room temperature in the laboratory. The second set were produced and demoulded after 24hrs and then left to cure in the oven at 85°C to simulate 10 years of ageing. Once the 5-day curing period was completed the samples were ready to be tested for ITSM. The ITSM testing was done in accordance with the BS EN 12697-26 at 20°C. The results were analysed to determine a SMR of the aged to unaged samples as a percentage.

SMR = (Aged ITSM / Control ITSM) × 100

HAN-CMA Results

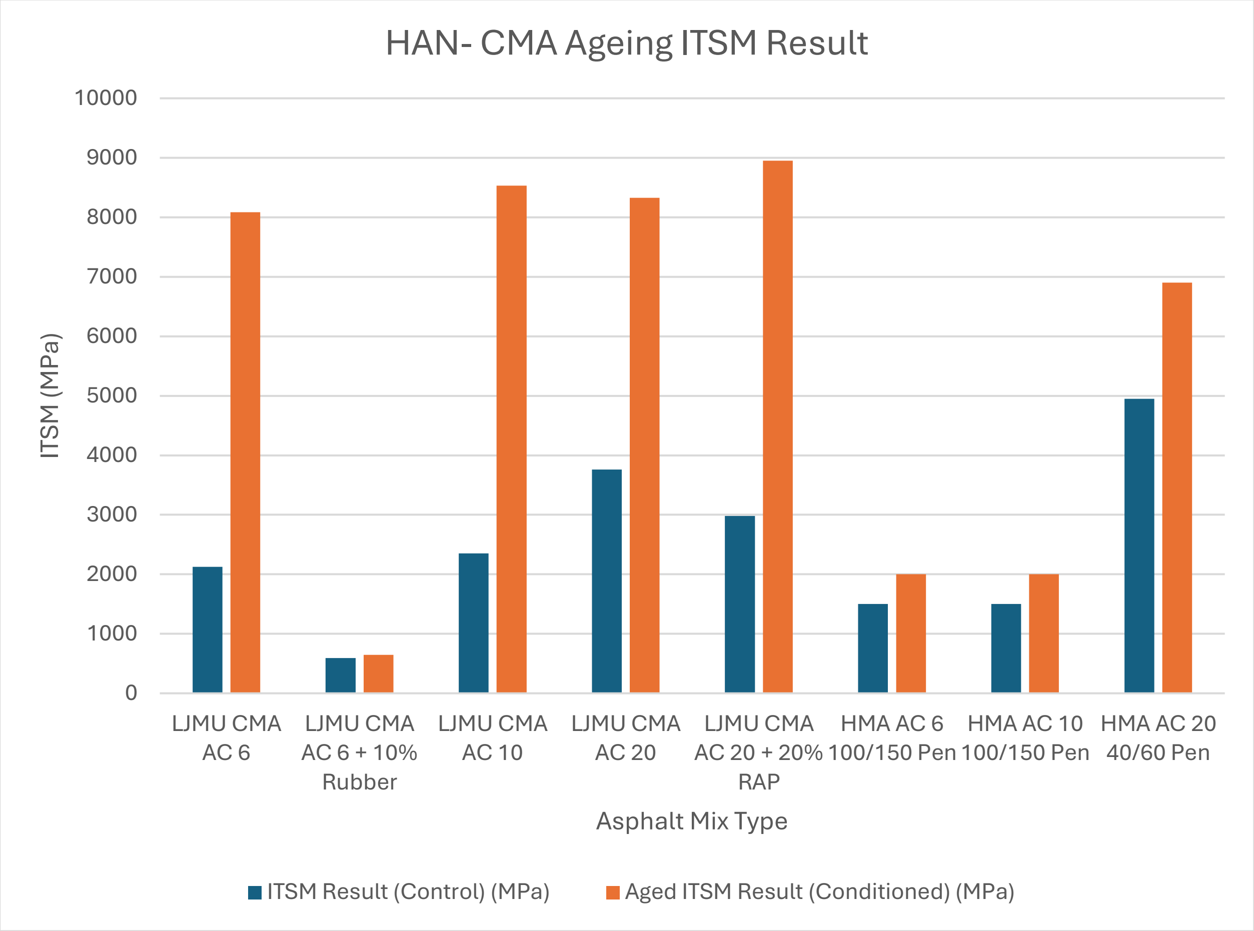

Figure 20. LJMU CMA (HAN-CMA) Ageing ITSM Result

HAN-AC 6 HAN-CMA Results

Figure 20 above shows that the ITSM results for the AC 6 HAN-CMA significantly increase after undergoing the ageing test to simulate 10 years of bitumen ageing. The Stiffness Modulus Ratio (SMR) is 380% with the unconditioned sample showing ITSM results of 2126MPa and the conditioned sample showing a result of 8086 MPa. The HMA AC6 still increases during the ageing test but the SMR is much lower than the AC 6 HAN-CMA. The HMA AC 6 has an SMR of 133%, this is due to the hardening process of the asphalt binder as the test temperature is elevated, and thus the viscosity of the asphalt binder Increases. The increase in stiffness for the new HAN-CMA is also, due to the increase of the hydration process within the filler due to the elevated temperature. This increases the rate of micro and macro crystals forming within the HAN-CMA mixture resulting in increased stiffness and overall strength (Dulaimi, 2016).

The new AC 6 with 10% rubber HAN-CMA show a lower SMR ageing index of 109% which is significantly lower than the new AC 6 CMA. The ITSM results show an increase from 590MPa to 645MPa. The reduced SMR index for the new AC 6 with 10% rubber is due to the swelling of the rubber crumb within the asphalt mixture. “During the long-time swelling process, rubber aging takes place, polar groups appear, and the glass transition temperature of rubber increases” where the rubber behaves more like glass than rubber resulting in little to no strength gain (Dong, D. *et al.* 2012).

AC 10 HAN-CMA Results

Figure 20 shows how the stiffness of the new AC 10 HAN-CMA significantly improves after undergoing the ageing test. The SMR or ageing index is seen to be 362% compared to the unconditioned ‘control’ mix. The ITSM of the unconditioned samples show a result of 2535MPa, whilst the conditioned samples reach to 8531MPa. The AC 10 HMA has an ageing Index of 133% where the control mix is roughly 1500MPa and the aged, conditioned samples reach 2000MPa.

AC 20 HAN-CMA Results

Figure 20 shows how both new AC 20 HAN-CMA and AC 20 with 20% RAP perform after simulating 10 years of bitumen ageing. After being conditioned in an oven at 85°C for 5 days, the ITSM results significantly improve. HAN-AC 20 HAN-CMA has an ageing index of 222% where the control has a result of 3759MPa and the aged samples have a result of 8329MPa. The AC 20 CMA-HAN with RAP has an ITSM result of 2979MPa for the control mix and 8951MPa when aged, with and SMR of 300%. Thus, proves that the LJMU mix design continues to grow in stiffness over its whole life span due to the secondary cementitious materials included in the mix design. The ageing index of the HMA is less than the CMAs once again, with a SMR of 139% where the ITSM results of the HMA is 4950MPa unconditioned and the aged sample reaches 6900MPa.

HAN- LHA Result

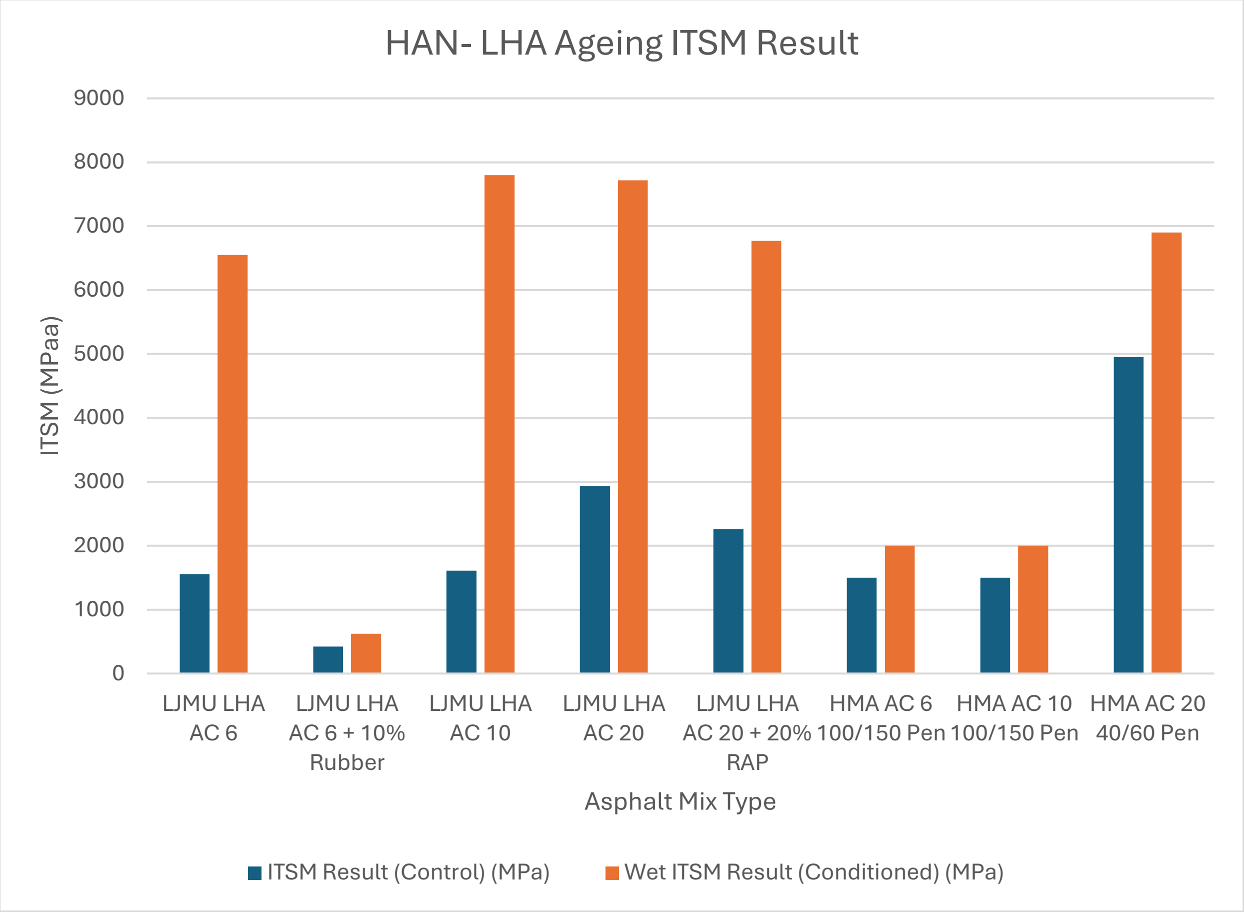

Figure 21. LJMU LHA (HAN-LHA) Ageing ITSM Result

AC 6 HAN-LHA Results

Figure 21 above shows that the ITSM results for the new AC 6 HAN-LHA significantly increases after undergoing the ageing test to simulate 10 years of bitumen ageing. The Stiffness Modulus Ratio (SMR) is 421% with the unconditioned sample showing ITSM results of 1550MPa and the conditioned sample showing a result of 6550MPa. The overall ITSM results of the unconditioned and aged samples are lower than the new AC 6 CMA samples, but the SMR is higher. The HMA AC6 results stay the same as mentioned in the new HAN-CMA ageing section. The HMA AC 6 has an SMR of 133% which is much lower than both the new AC6 HAN-CMA and HAN-LHA.

The HAN- AC 6 with 10% rubber LHA showed a reduced ITSM result compared to AC 6 with 10% rubber HAN-CMA. The ITSM result of the unconditioned sample was 424 MPa, while the aged sample was 625 MPa, giving an SMR of 147%. Showing increased stiffness gain compared to the HAN-CMA, which had an SMR of 109%.

AC 10 HAN-LHA Results

The SMR index for the AC 10 HAN-LHA is 484.5% showing a substantial stiffness gain from 1600MPa to 7800MPa after being subject to the ageing conditions to simulate 10 years of bitumen ageing. The unconditioned and conditioned samples of the AC 10

HAN-CMA is higher with ITSM results, 2353MPa and 8531MPa respectively. The new AC 10 HAN-CMA gives and SMR index of 363%, showing that there is likely to be higher stiffness gain in the new AC 10 HAN-LHA over 10 years of curing.

AC 20 HAN-LHA Results

The new AC 20 LHA show an increase of stiffness from 2950MPa to 7725MPa between the unconditioned and aged conditioned samples, resulting in an SMR index of 263%. The new AC 20 HAN-CMA results have a higher unconditioned stiffness of approximately 3750MPA and an SMR of 222%.

The AC 20 HAN-LHA with 20% rubber shows a reduced unconditioned and conditioned ITSM result of, 2250MPa and 6750 MPa respectively, with an SMR index of 300%. The new AC 20 with 20% rubber HAN-CMA has higher overall ITSM results, this time the SMR index is the same at 300%.

The ITSM results of the new LHA are all lower than the HAN-CMA materials, but all (except AC 20 with 20%RAP) have a higher SMR ageing index. This suggests that the new HAN-LHA has an overall reduction in stiffness compared to the new HAN-CMA, this may be due to higher residual moisture trapped within the samples due to the rapid surface hardening as the aggregates are heated to 60°C. This would also explain the increased SMR ageing index in LHA as the ageing process will allow the trapped moisture to evaporate, resulting in more effective curing.

Air Void & Bulk Density

Figure 22 below shows the air voids content and the bulk density of the asphalt samples prepared in the LJMU laboratory according to BS EN 12697-5 to calculate the maximum theoretical density of the samples, BS EN12697-6 to calculate the measured bulk density of the samples, BS EN 12697-8 to measure the air void content of the samples.

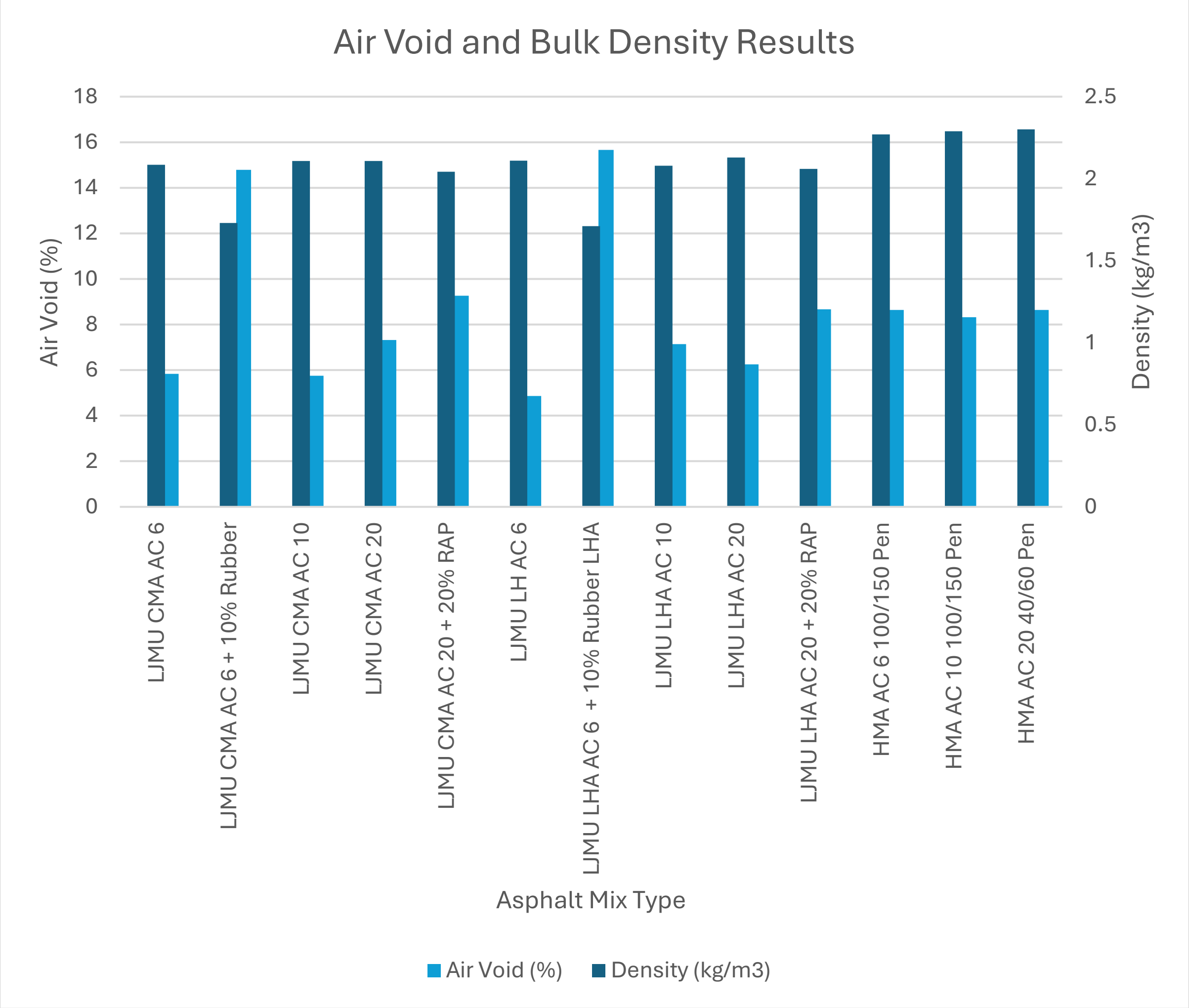

Figure 22. LJMU HAN-CMA & HAN-LHA Air Void and Bulk Density Results

- The HMA mixtures all show similar density and air void content, the density increases fractionally as the aggregate sizing in the mix increases. HMA AC6 has a density of 2.27kg/m3 and air void content of 8.64%, HMA AC 10 has a density of 2.29kg/m3 and air void content of 8.32%, HMA AC 20 has a density of 2.3kg/m3 and air void content of 8.64%.
- The HAN-CMA mixes all have a lower density than the HMA ranging from 2.042kg/m3 to 2.108kg/m3. This is due to the low density secondary cementitious materials included in the filler and the higher water content of the LJMU modified mixtures.
- HAN-CMA AC 6 with 10% rubber shows low density and high air voids, along with the low dense LJMU filler material and high-water content, the rubber crumb has

a low density and pockets of air in their centre leading to the higher air void content.

- HAN-LHA mixes showed similar results to the HAN-CMA mixes for both their densities and air void content. This was expected as the same materials were used in both mix designs. The only expected difference was a slightly lower air void content in the LHA, attributed to increased compaction, densification, hydration and the formation of macro and micro crystals within the mix as a result of elevated temperatures. This is true for the HAN- LHA mixes with reduced air voids in HAN-LHA AC 6, HAN-LHA AC 20 and HAN-LHA AC 20 with 20% RAP.

HAN-CMA Bulk Density and Air Void Contents - LJMU Laboratory Results compared with XAIS-PTS Independent Laboratory Results

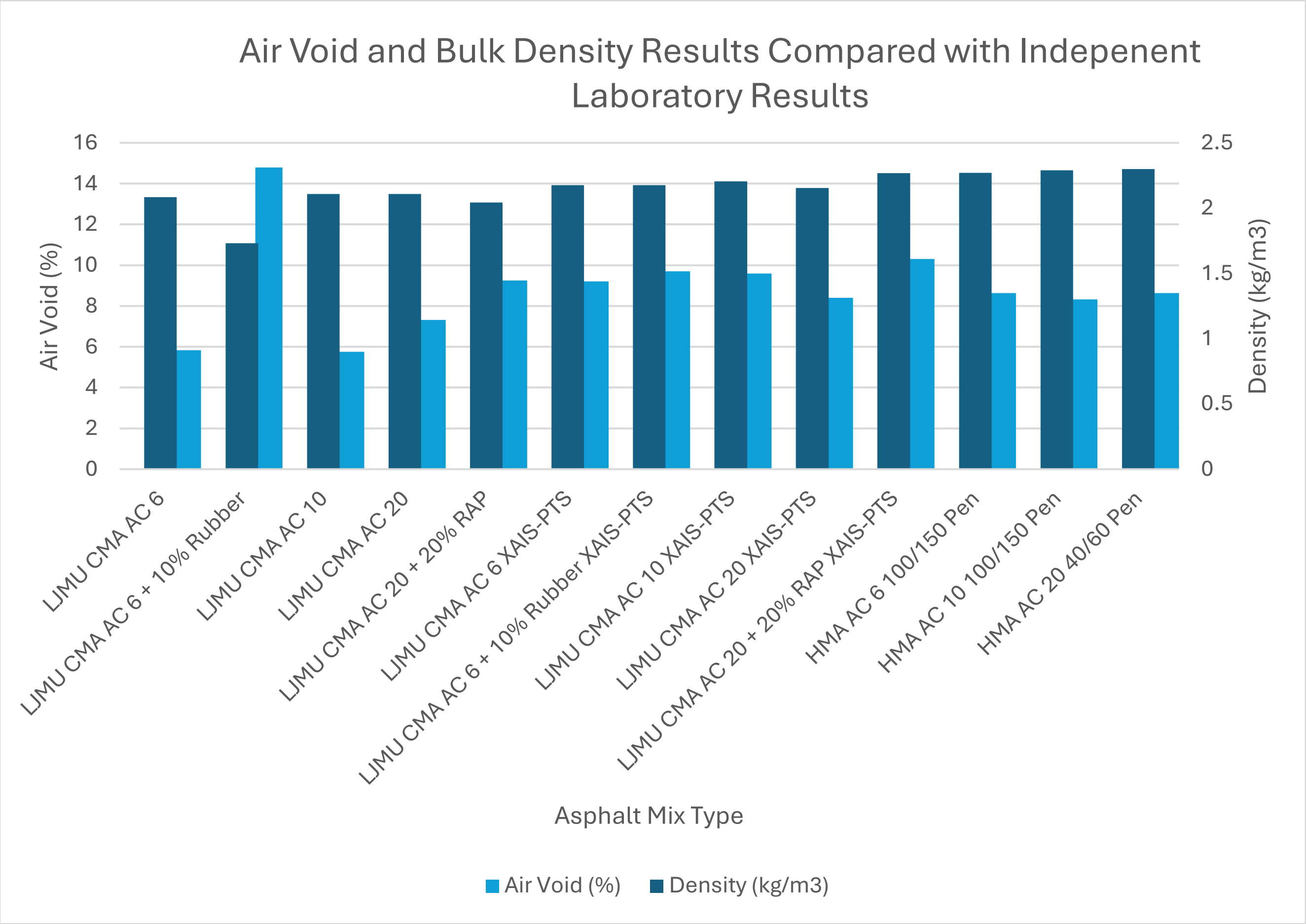

Figure 23. HAN-CMA Air Void and Bulk Density Results compared to XAIS-PTS Independent Laboratory Result

Again, the HAN- CMA samples were sent to the independent laboratory, XAIS-PTS, in Preston for the bulk density and air void calculation testing.

- The HAN- CMA results were similar between both testing facilities, with LJMU laboratory results showing densities between 2.042kg/m3 to 2.108kg/m3 (excluding the HAN-AC 6 with 10% rubber). The independent, XAIS-PTS laboratory, showed slightly higher densities between 2.176kg/m3 to 2.267kg/m3.
- The air void results from the independent laboratory were higher than the LJMU laboratory. XAIS-PTS had results between 9.2% air void content and 10.3% air void content for all HAN-CMA samples. LJMU laboratory showed results of 5.8% to 9.3% air void content for all HAN-CMA samples (excluding AC 6 HAN-CMA with 10% rubber CMA).
- AC 6 HAN- CMA with 10% rubber was the main differential in air void and bulk density results between both laboratories. The new mixtures had a measure bulk density of 2.042kg/m3 and air void content of 14.8%, whilst XAIS-PTS showed results of 2.176kg/m3 and air void content of 9.7%.

Leachate of Heavy Metals Test

The Toxic Characteristic Leaching Procedure (TCLP) is used to determine if the bituminous material could leach hazardous concentrations of heavy metals into the surrounding environment. In this test the TCLP was used to assess the leached concentrations of Nickel (Ni), Copper (Cu), Lead (Pb), Chromium (Cr), Zinc (Zn), Strontium (Sr), Barium (Ba) and Cadmium (Cd) from the HAN-LHA and HAN-CMA samples.

The LJMU samples were crushed in the laboratory ready to be tested. A stock of TCLP leachate was prepared by mixing stoichiometric amounts of deionised water and acetic acid (pH 2.88). 10g of the crushed samples were placed in bottles containing 200 mL of the TCLP leachate. These bottles were then shaken using a rotary extractor at 30 rpm for 18hrs. The testing was all carried out at 20°C. After the extraction process, the solutions were filtered using a 47-mm glass fibre filter, then acidified using acetic acid to a pH below 2. The concentrations of heavy metals were measured using an atomic Ab sorption spectrophotometer (type: Thermo, model: ICE 3300).

The concentrations of heavy metals, Ni, Cu, Pb, Cr, Zn, Sr, Ba and Cd in the leachates were predicted according to the TCLP test, are tabulated in Table 6. All the metals concentrations are less than the regularity standard levels, the minimum limits to classify the hazardous materials. Based on these results, it can be stated that not only did the inclusion of the LJMU HAN-SCM used as filler in the HAN-CMA and HAN-LHA mixtures have technical advantages, helped by accommodating waste by-products, the filler material also decreased potentially harmful effects on the environment.

Table 5. Leachate of Heavy Metals Result

Heavy metal concentration (mg/L)	Reference water quality	LJMU Filler	TCLP regulatory level
Nickel (Ni)	0.0	3.312	25
Copper (Cu)	0.0	0.016	25
Lead (Pb)	0.0	0.047	5
Chromium (Cr)	0.0	0.0112	0.05
Zinc (Zn)	0.0	-	25
Strontium (Sr)	0.0	0.521	4
Barium (Ba)	0.0	-	100
Cadmium (Cd)	0.0	-	1

Bitumen emulsion and allied hydration process are an active stabilisation and solidification agent for heavy metals meaning that leachates will not have any harmful effects on underground and surface water resources. The results remain the same for the LJMU HAN-CMA and HAN-LHA as they are made from the same materials.

Newsham Park Trial Monitoring Results

The trial site in Newsham Park, Liverpool post code L6 7UN, was completed and subjected to 2 site visits where the licensed testing company Celtest carried out required testing to determine the performance of the different asphalt materials.

The monitoring programme of the trial sections will be as follows:

- Volumetric Patch test conducted by licenced company to provide a measurement of surface texture depth of the trial sections after 1 month and 6 months.
- Relative Hydraulic Conductivity test conducted by licenced company.
- Pendulum skid resistance test conducted by licenced company.
- Indirect Tensile Stiffness Modulus of cores taken from trials sections done by LJMU.
- Air Void and Bulk Density calculations of cores taken from trials section done by LJMU

Volumetric Patch Test

The volumetric patch test is a measurement of a pavements surface macrotexture depth. This test was carried out following BS EN 13036-1(2010). This test is used to determine the average macrotexture depth of a pavement surface, following the 'sand patch method.

The sand-patch method has been used worldwide for many years to measure the road surface texture. It relies on a given volume of sand which is spread out on a road surface. The sand is distributed to form a circular patch on the dry surface of the pavement, and the diameter is then measured. By dividing the volume of sand with the area covered, a value is obtained which represents the average depth of the sand layer (BS EN 13036-1, 2010) within the area covered by the sand filling the voids in the surface of the asphalt layer. This value is the pavement macrotexture depth, which can be used to determine the pavement skid resistance capability, noise characteristics and the suitability of paving materials or finishing techniques.

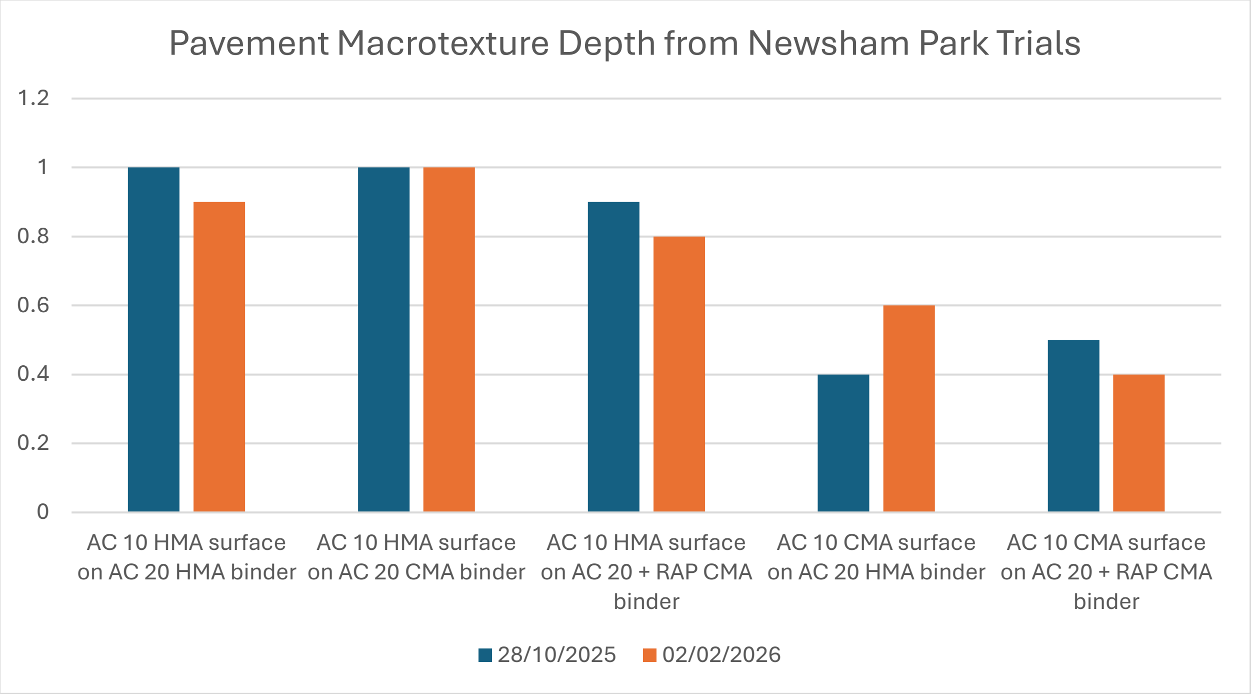

Figure 24. Pavement Macrotexture Depth from Newsham Park Trials. (Trial constructed on end of July 2025)

The volumetric patch test was carried out by Celtest ltd accredited testing company in accordance with the BS EN 10363-1 (2010) at the Trial site. UK highway specifications state that a minimum texture depth of 1mm is required for high-speed roads, 0.8mm for lower street roads and 0.6mm for other bituminous surfaces (DfT, 2019).

- Section 1, The AC 10 HMA surface with an AC 20 HMA binder shows macrotexture depth of 1.0mm for the first site visit, and 0.9mm for the second visit.
- Section 2, The AC 10HMA surface on AC 20 HAN- CMA binder, shows macrotexture of 1.0mm for the first and second trial visit.
- Section 3, The AC 10 HMA surface on AC 20 + 20% RAP HAN-CMA binder, with an initial macrotexture depth of 0.9mm for the first trial visit and 0.8mm for the second trial visit.
- Section 4, AC 10 HAN-CMA surface on AC 20 HMA has reduced macrotexture compared to the HMA. The first site visit showed macrotexture depth of 0.4mm and the second site visit showed macrotexture depth of 0.6mm.
- Section 5, AC 10 HAN-CMA surface on AC 20 + 20% RAP HAN-CMA binder, shows a macrotexture depth of 0.5mm for the first site visit and 0.4mm for the second site visit.

The macrotexture results indicate that the trial sections constructed with AC 10 HMA surface courses exhibited greater surface texture depth compared to those with the AC 10 HAN-CMA surface courses. Sections 1 to 3 recorded macrotexture depths ranging from approximately 0.8 mm to 1.0 mm across both site visits, demonstrating suitability for all types of roads and highway construction in the UK. In comparison, Sections 4 and

5, which used the HAN- CMA surface courses, produced noticeably lower macrotexture depths, ranging between 0.4 mm and 0.6 mm. The results below 0.6mm are below the minimum requirement for bituminous surfaces in the UK. The LJMU and Henry Williams and Son team did provide a seal coat on the HAN- CMA sections which is likely to have reduced the texture depth of the surface. The higher macrotexture values observed in the HMA sections suggest improved surface texture characteristics, which are beneficial for water drainage and tyre–pavement interaction. Overall, these findings indicate that HMA surface courses provide more pronounced macrotexture than HAN-CMA surfaces, while HAN-CMA sections may exhibit lower initial texture depths that could change with trafficking and environmental exposure over time. Further research should be done by LJMU on the seal coat finish, to improve the texture depth.

Hydraulic conductivity test

The relative conductivity test is executed by Celtest ltd and normally used to determine the pavements' ability to drain water. This test can be used as a compliance check to ensure that a permeable surface course has the required properties when it is laid. The test follows BS EN 12697-40 (2020) and can be conducted in wet or dry conditions as long as the surface of the asphalt is not frozen and cleared of any debris. The test operates using a radial flow falling head permeameter, which is initially filled with 5 litres of water. The hydraulic conductivity is determined by measuring the time (in seconds) required for 4 litres of water to infiltrate through the annular surface section of the pavement.

The hydraulic conductivity is determined by measuring the time (in seconds) and all the results are within the limits accepted by the current regulations.

Pendulum skid resistance

The pendulum skid resistance test follows BS EN 13036-4 (2011) and is the standardised method carried out by Celtest ltd to determine skid resistance of the macrotexture of an asphalt pavement surface. The test is performed using a pendulum apparatus equipped with a standardized rubber slider that is released to swing over a fixed length of the surface, with the loss of energy caused by friction between the slider and the surface, recorded on a calibrated scale. The value provided on the scale is known as the Pendulum Test Value. The higher the PTV, the greater the surface skid resistance. This value reflects the surface's ability to provide traction for vehicle tyres and pedestrian footwear, particularly under wet conditions. In pavement engineering, the test is significant because it indicates the surface friction characteristics that influence road safety, braking performance, and the risk of skidding.

The test procedure must be done on a section of the pavement surface that has been brushed free from any debris to ensure no interference with the test results. The pendulum should swing in the direction of the traffic, and the gradient of the asphalt pavement should not exceed 10%. Before conducting the temperature of the surface will be measured and should not exceed 5°C - 40°C. Also, the temperature of the surface after being wetted needs to be measured, if the water temperature differs to the air temperature by 15°C the testing cannot be conducted.

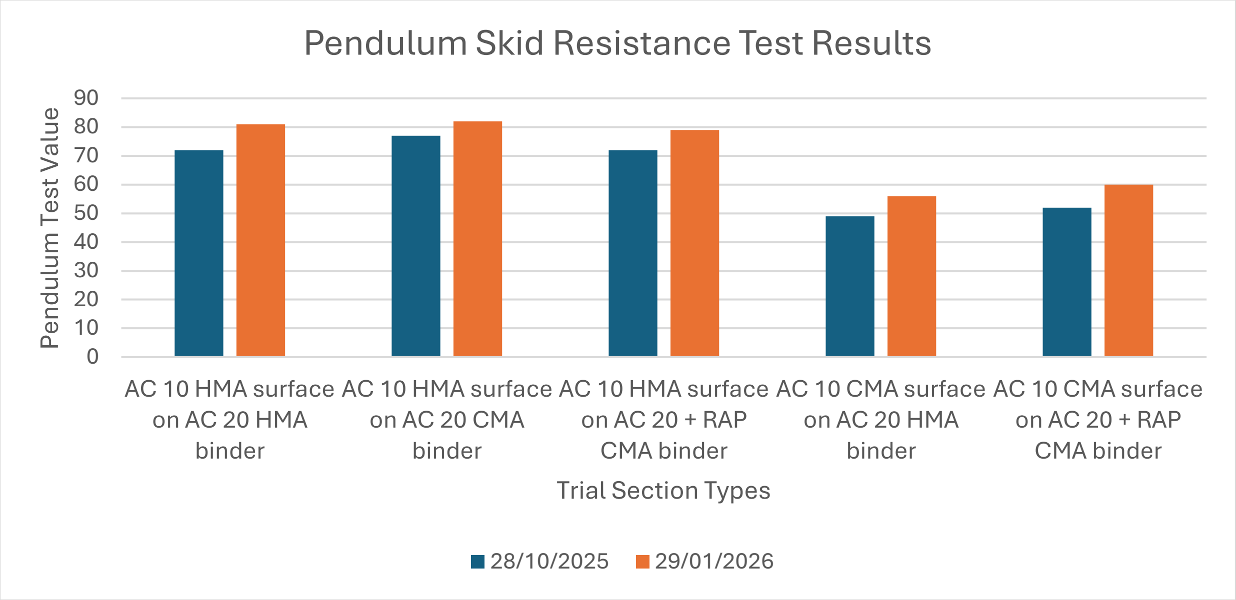

Figure 25. Pendulum Skid Resistance Test Result from Newsham Park Trials. Trial constructed on end of July 2025

These results seen in figure 25, were obtained by Celtest ltd, to determine the skid resistance of the trial sections.

Skid resistance was measured using the pendulum test in accordance with BS EN 13036-4. Typical guidance values suggest minimum pendulum test values of approximately 45 for low risk sites, 55 for heavily trafficked roads, and 65 for high risk locations such as junction approaches (DMRB CS 225).

- Section 1, The AC 10 HMA surface with an AC 20 HMA binder shows excellent skid resistance with a PTV over 70 for the first site visit, and 80 for the second visit.
- Section 2, The AC 10HMA surface on AC 20 HAN-CMA binder, shows great skid resistance values over 75 for the first site visit, over 80 for the second trial visit.
- Section 3, The AC 10 HMA surface on AC 20 + 20% RAP HAN-CMA binder, with an initial PTV of 70 on the first trial visit and below 80 for the second trial visit.
- Section 4, AC 10 HAN-CMA surface on AC 20 HMA has a reduced skid resistance compared to the HMA. The first site visit showed PTV results below 50, and the second site visit showed PTV results over 55.
- Section 5, AC 10 HAN-CMA surface on AC 20 + 20% RAP HAN-CMA binder, shows a PTV value of over 50 for the first site visit and 60 for the second site visit.

Overall, the skid resistance results demonstrate that sections incorporating HMA surface courses consistently produced higher Pendulum Test Values (PTV) than those constructed with HAN- CMA surface courses. Sections 1 to 3, which used AC 10 HMA surfaces, showed excellent skid resistance across both site visits, with PTV values ranging from approximately 70 to above 80. This indicates a high level of exposed aggregate micro texture and strong frictional performance. Sections 4 and 5, which utilised AC 10 HAN-CMA surface courses, exhibited lower skid resistance values, although an improvement was observed between the first and second site visits. The increase in PTV values during the second visit may be attributed to trafficking and environmental effects gradually exposing aggregate micro texture as the binder film wears. The LJMU and Henry Williams and Son team did provide a seal coat on the HAN-CMA sections which may have negatively affected the results for the skid resistance. Overall, the results suggest that while HAN-CMA surfaces can achieve acceptable levels of skid resistance over time, HMA surface courses provide superior initial skid resistance performance.

Coring for ITSM, air voids and bulk density

In order to test the structural performance of the trial sections 100mm cores were extracted and tested at the LJMU laboratory. 3 cores from each chosen trial section were tested for indirect tensile stiffness modulus to give an indication to the strength of the material in a real-world environment. Following this, air void and bulk density calculations will be taken and compared with the laboratory results. Results of both the ITSM, air voids and bulk density calculations will be compared with the laboratory results. This will give an indication on how the material is affected by the real road surfacing environment, if the material was mixed and compacted to a high standard.

The coring only took place on the 'cycle path' section of the trial due to implications when following the British standards for the ITSM testing. BS EN 12697-26 states "The cylinder shall be clamped in the jig and sawn into slices with a thickness in the range 30 mm to 75 mm, each slice constituting a specimen". The nominal thickness of the surface for the 'walkway' trial section is 20-25mm and therefore is too small to undergo the ITSM testing. This means that the results for the AC 6 will not be available for HMA or HAN- CMA.

The cores were taken from trial 2: section 1, section 2 and section 5.

- Section 1 is the control mix as the surface course is 40mm of AC 10 HMA (100/150 pen) on a binder course of 50mm AC 20 HMA (40/60 pen).
- Section 2 is partial carbon saving as the surface course 40mm of AC 10 HMA (100/150 pen) on a binder course 50 mm of AC 20 HAN-CMA.
- Section 3 is a full carbon saving as the surface course is 40mm of AC 10 HAN- CMA on binder course 50m of AC 20 HAN-CMA.

These three sections were chosen in order to understand the effect of each different combination of surface layers mixtures, full HMA, partial HMA and full LJMU CMAs. This allows us to compare the results to the control mix. See if the material performs differently with different binder course to surface course combinations.

ITSM Results from Newsham Park Trial

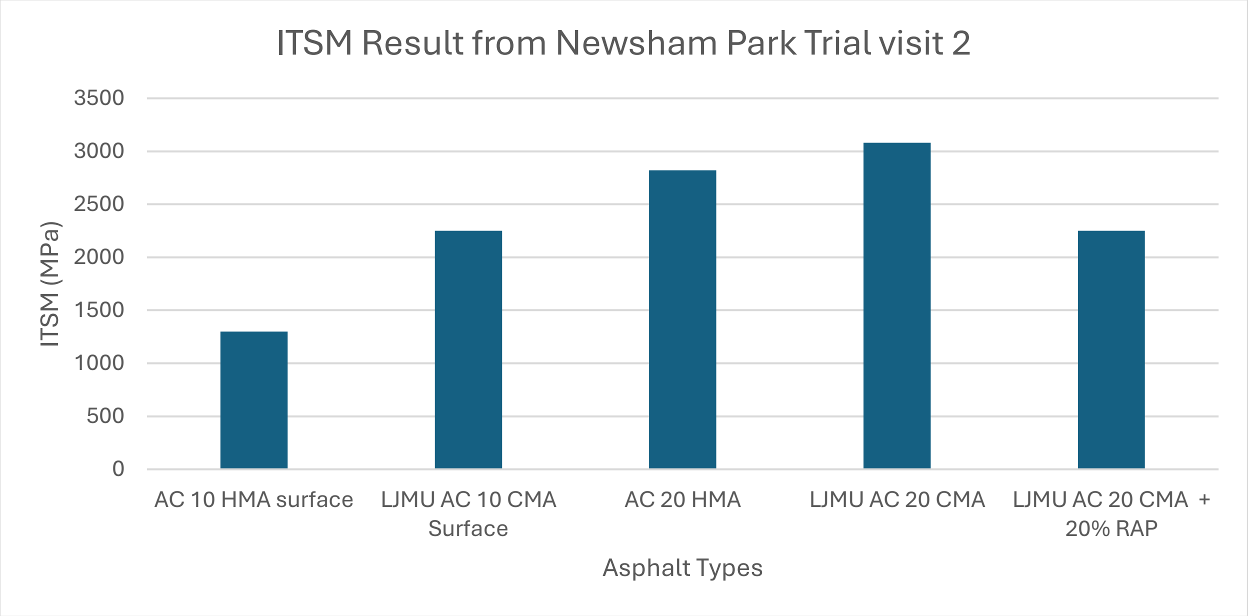

Figure 26. ITSM Result from Newsham Park Trial

Figure 26 above shows the ITSM results from the cored samples at Newsham Park, Liverpool, UK. The coring was completed by Celtest ltd and the ITSM testing was conducted in the LJMU laboratory.

- AC 10 HMA, has a value of 1300MPa which is lower than expected. The value of The AC 10 HMA was roughly 2000MPa produced in the LJMU laboratory. The HMA has a stiffness lower than the target minimum 1500MPa.
- The AC 10 HAN-CMA has an ITSM result of 2250MPa, showing greater results than the AC 10 HMA and the 1500MPa minimum target.
- The AC 20 HMA has an ITSM result over 2800MPa, this is greater than the 2500MPa minimum target but lower than the samples produced the LJMU laboratory which are giving ITSM result of 4900MPa
- The AC 20 HAN- CMA, shows greater ITSM results than the AC 20 HMA samples with ITSM of 3080MPa. This is greater than the target set at 2500MPa.
- The AC 20 + 20% RAP HAN-CMA shows results of 2250MPa, which is lower than the target of 2500MPa. This is lower than both AC 20 HAN-CMA and HMA.

The Indirect Tensile Stiffness Modulus (ITSM) results obtained from the cored samples show varying stiffness performance between the different mixtures. The AC 10 HMA recorded an ITSM value of 1300 MPa, which is lower than the expected value and below the target minimum of 1500 MPa. This is also significantly lower than the approximately 2000 MPa measured for similar samples produced in the LJMU laboratory, indicating that the in-situ material may have experienced reduced stiffness due to factors such as poor compaction. In contrast, the AC 10 HAN-CMA exhibited a higher stiffness modulus of 2250 MPa, exceeding both the AC 10 HMA result and the minimum target requirement. For the binder course mixtures, the AC 20 HMA achieved an ITSM value of over 2800 MPa, which satisfies the minimum target of 2500 MPa, although it remains significantly lower than the 4900 MPa measured for the samples produced at the LJMU laboratory. The AC 20 HAN-CMA demonstrated the highest stiffness among the binder mixtures with an ITSM of 3080 MPa, exceeding both the target requirement and the AC 20 HMA result. Finally, the AC 20 HAN-CMA with 20% RAP produced an ITSM value of 2250 MPa, which falls below the 2500 MPa target and is lower than both the AC 20 HAN-CMA and AC 20 HMA mixtures. This indicates that the in-situ material may have experienced reduced stiffness due to poor compaction as discussed above. Some cores experienced cracking during the drilling and extraction process, which may have affected the stiffness of the samples and potentially affected the test results.

Bulk Density and Air void Calculations from Newsham Park Trials

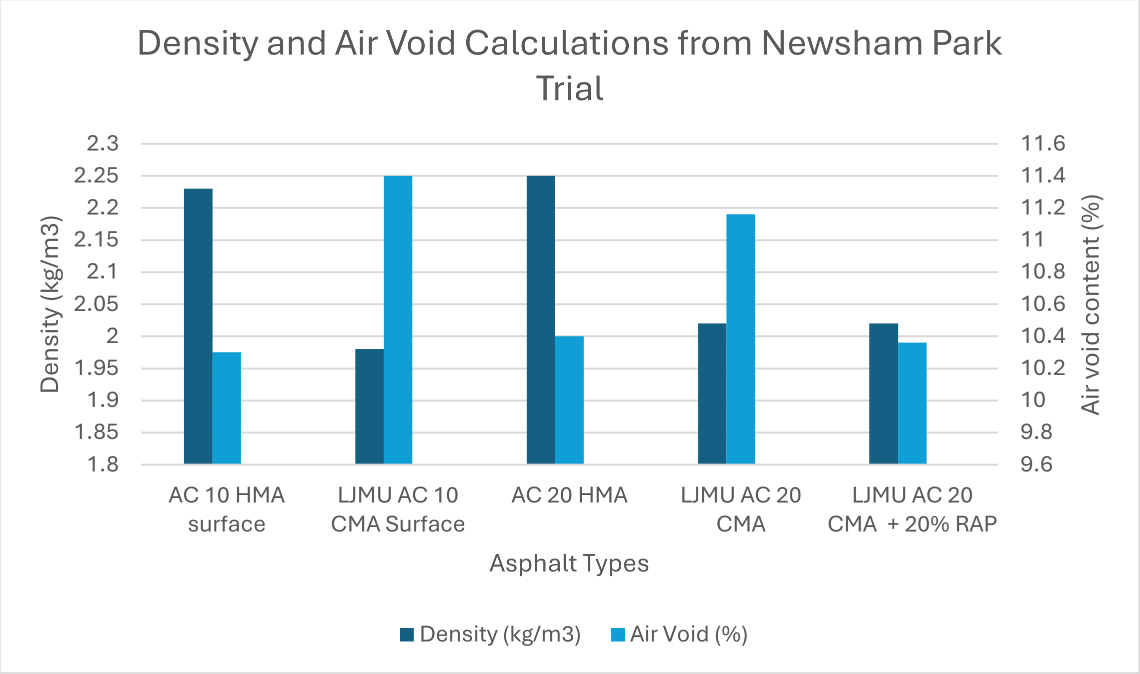

Figure 27.Bulk Density and Air Void Calculations from Newsham Park Trials

Figure 27 shows the results of the Bulk density and Air void calculation from the trials, the testing was done at the LJMU laboratory and followed in accordance with BS EN 12697-5 to calculate the maximum theoretical density of the samples, BS EN12697-6 to calculate the measured bulk density of the samples, BS EN 12697-8 to measure the air void content of the samples.

- The AC 10 HMA, shows results of 10.3% air void content and a bulk density of 2.23Kg/m3. The density of the AC 10 HMA is lower from the cored samples compared to the samples produced at LJMU laboratory, which showed a density of 2.29Kg/m3 and air void content of 8.3%
- The AC 10 HAN-CMA shows a bulk density of, 1.98Kg/m3 and air void content of 11.4%. Results from the AC 10 HAN-CMA samples produced at the LJMU laboratory show results of 2.11Kg/m3 and air void content 5.76%

- The AC 20 HMA, shows a bulk density of 2.25Kg/m3 and air void content 10.4%. The AC 20 HMA produced at the LJMU laboratory results show a higher density of 2.3Kg/m3 and a lower air void content of 8.6%.
- The AC 20 HAN-CMA show a bulk density of 2.02Kg/m3 and air void content of 11.17%. The samples produced at the LJMU laboratory show bulk density of 2.11Kg/m3 and air void content of 7.3%.
- The AC 20 HAN-CMA with 20% RAP show a bulk density of 2.02Kg/m3 and an air void content of 10.3%. The results from the samples produced at the LJMU laboratory show a density of 2.04Kg/m3 and an air void content of 9.3%.

Overall, the cored samples from the trial site showed lower bulk densities and higher air void contents compared with the samples produced in the LJMU laboratory. This trend was observed for both HMA and HAN-CMA mixtures, suggesting that the materials placed on site were less compacted than the laboratory prepared samples. The HAN-CMA mixtures exhibited the lowest densities and highest air void contents, while the mixtures containing 20% RAP produced results closer to the laboratory values. These differences likely reflect the influence of construction conditions and compaction variability in the field, which can result in higher air void contents compared with materials produced under controlled laboratory conditions.

Carbon Emissions Calculation

The carbon emission calculation presents a comparative analysis of carbon emissions associated with different asphalt materials and construction processes used at the Newsham Park trial, Liverpool UK. The carbon emissions calculation was done by Colas using carbon calculations using the FHRG Carbon Profiler. The calculation focuses on two primary material types: traditional hot mix asphalt (HMA) and the Liverpool John Moores University modified cold mix asphalt (HAN-CMA). The HAN-CMA material is also incorporating recycled asphalt pavement (RAP) and recycled rubber crumb into the design mix.

To provide a comprehensive assessment, emissions have been categorised into three key stages: *materials, transport, and plant operations*. The materials category accounts for emissions associated with the production of asphalt mixtures and constituent components. Transport emissions consider the impact of delivering raw materials, transportation of equipment and staff to the trial site. The plant emissions relate to on-site construction activities, including mixing, laying, and compaction.

The trial is structured across multiple sections, comprising both walkway and cycle path applications, with variations in surface and binder course materials. The primary distinction between these applications lies in the aggregate sizes used: AC 6 for walkway surface courses, AC 10 for cycle path surface courses, and AC 20 for binder courses in both cases. This approach enables direct comparison between HMA and HAN- CMA solutions, while also allowing evaluation of the influence of recycled content and material sourcing on overall carbon performance.

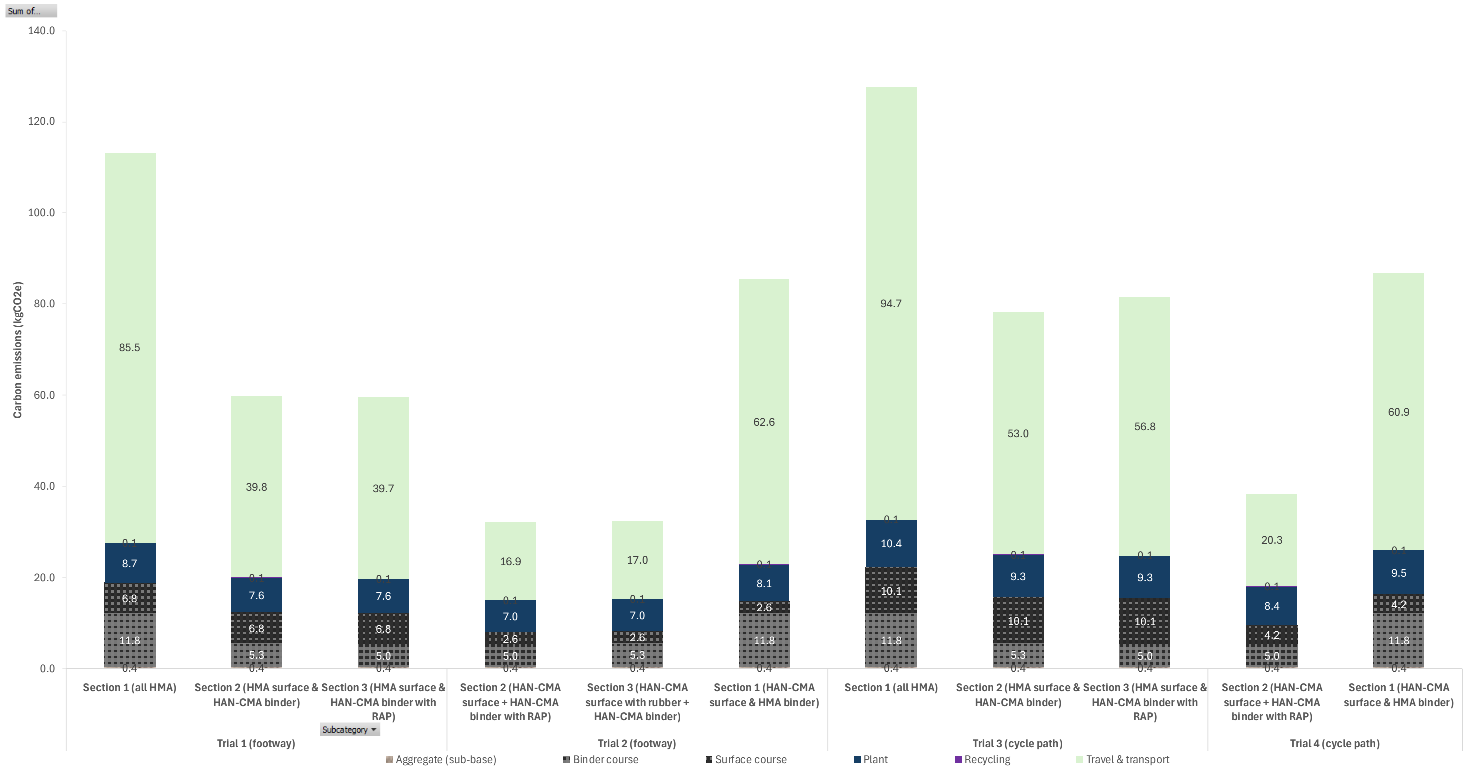

Figure 28. *Carbon Calculation from Newsham Park Trials*

The figure 28 above shows the embodied carbon emission (kgCO2e) results from the Trial at Newsham Park Liverpool. The figure shows the embodied carbon emissions from each trial section, which is shown in more detail below:

Trial 1,

- Section 1: 1.5m in length, 25mm layer of 0/6mm AC HMA surface course on 50mm layer 0/20mm AC HMA binder course.
- Section 2: 1.5m in length, 25mm layer of 0/6mm AC HMA surface course on 50mm layer 0/20mm AC HAN-CMA binder course.
- Section 3: 1.5m in length, 25mm layer of 0/6mm AC HMA surface course on 50mm layer 0/20mm HAN-CMA binder.

Trial 2,

- Section 1: 1.5m in length, 25mm layer of 0/6mm AC HAN-CMA surface course on 50mm layer 0/20mm AC HMA binder course.
- Section 2: 1.5m in length, 25mm layer of 0/6mm AC HAN-CMA surface course on 50 mm layer 0/20mm HAN-CMA binder course with 20% RAP.

- Section 3: 1.5m in length, 25mm layer of 0/6mm AC HAN-CMA with 10% fine rubber crumb surface course on 50 mm layer 0/20mm AC HAN-CMA binder course.

Trial 3,

- Section 1: 1.5m in length, 40mm layer of 0/10mm AC HMA on 50mm layer AC 0/20mm HMA binder course.
- Section 2: 1.5m in length, 40mm layer of 0/10mm AC HMA on 50mm layer AC 0/20mm HAN-CMA binder course.
- Section 3: 1.5m in length, 40mm layer of 0/10mm AC HMA on 50mm layer AC 0/20mm HAN-CMA binder course with 20% RAP.

Trial 4,

- Section 1: 1.5m in length, 40mm layer of 0/10mm AC HAN-CMA on 50 mm layer AC 0/20mm HAN-CMA binder course.
- Section 2: 1.5m in length, 40mm layer of 0/10mm AC HAN-CMA on 50 mm layer AC 0/20mm HAN-CMA binder course with 20% RAP.

The figure is broken down into key lifecycle components including aggregate, binder course, asphalt plant energy consumption, recycling process and transportation. This breakdown allows us to assess the contribution of each component to the total carbon footprint of each trial section.

Total Carbon Emissions

The results clearly show differences in total carbon emissions due to the different asphalt materials used at the Trial Site in Newsham Park, Liverpool.

Trial 1. Walkway (HMA surface)

- Section 1: This section uses HMA for both the surface and binder courses, resulting in the highest carbon emissions within the 'walkway' trial. Total emissions are approximately 113.2 kgCO$_2$e.

- Section 2: This section uses an HMA surface with LJMU AC 20 HAN-CMA as the binder course. Replacing the traditional HMA binder with HAN-CMA reduces total emissions to approximately 59.9 kgCO$_2$e, representing a carbon saving of 47.1%.

- Section 3: This section uses an HMA surface with LJMU AC 20 + 20% RAP HAN-CMA as the binder course. Total emissions are approximately 59.6 kgCO$_2$e, a marginal reduction of 0.3 kgCO$_2$e compared to Section 2. This equates to a 47.4% saving relative to Section 1.

Trial 2. Walkway (LJMU HAN-CMA surface)

- Section 1: This section uses LJMU AC 6 HAN-CMA as the surface course with an AC 20 HMA binder course, resulting in total emissions of 62.6 kgCO$_2$e. This represents a 24.3% reduction compared to the full HMA section (Trial 1, Section 1).

- Section 2: This section uses LJMU AC 6 HAN-CMA as the surface course with LJMU AC 20 + 20% RAP HAN-CMA as the binder course. Total emissions are 32.0 kgCO$_2$e, delivering a 71.7% reduction compared to the walkway HMA baseline (Trial 1, Section 1).

- Section 3: This section uses LJMU AC 6 HAN-CMA with 10% rubber crumb as the surface course and LJMU AC 20 HAN-CMA as the binder course. Total emissions are 32.4 kgCO$_2$e (0.2 kgCO$_2$e higher than Section 2). This slight increase is likely due to transport impacts associated with sourcing rubber from Portugal; emissions could be reduced with a local supplier. Overall, this section achieves a 71.4% reduction compared to the walkway HMA baseline.

Trial 3. Cycle Path (HMA surface)

- Section 1: This section uses AC 10 HMA as the surface course over an AC 20 HMA binder course, with total emissions of 127.5 kgCO$_2$e. This represents a 12.7% increase compared to the walkway HMA baseline (Trial 1, Section 1), likely due to the increased surface course thickness (40 mm vs. 25 mm).

- Section 2: This section uses AC 10 HMA as the surface course with LJMU AC 20 HAN-CMA as the binder course. Total emissions are 78.1 kgCO$_2$e, equating to a 38.7% reduction compared to the Cycle Path HMA baseline (Trial 3, Section 1).

- Section 3: This section uses AC 10 HMA as the surface course with AC 20 + 20% RAP as the binder course. Total emissions are 81.7 kgCO$_2$e, which is 3.6 kgCO$_2$e higher than Section 2. Although recycled material is used, the increase is attributed to higher transport emissions associated with RAP. This section still achieves a 35.9% reduction compared to the Cycle Path HMA baseline.

Trial 4. Cycle Path (LJMU HAN-CMA surface),

- Section 1: This section uses LJMU AC 6 HAN-CMA as the surface course with an AC 20 HMA binder course. Total emissions are 86.9 kgCO$_2$e, representing a 31.9% reduction compared to the Cycle Path HMA baseline (Trial 3, Section 1).

- Section 2: This section uses LJMU AC 6 HAN-CMA as the surface course with LJMU AC 20 + 20% RAP HAN-CMA as the binder course. Total emissions are 38.4 kgCO$_2$e, resulting in a 69.9% reduction compared to the Cycle Path HMA baseline (Trial 3, Section 1)

Across all trials, replacing traditional HMA with LJMU HAN-CMA in binder and/or surface courses consistently reduces carbon emissions. The greatest savings are achieved when LJMU HAN-CMA is used in both layers, particularly when combined with 20% RAP, with reductions of up to 71.7% compared to full HMA sections. However, the benefits of recycled materials can be offset by increased transport emissions, seen for both the 20% RAP and for the 10% rubber crumb replacement, highlighting the importance of local sourcing. Additionally, structural design factors such as layer thickness significantly influence total emissions, as seen in the higher impacts for cycle path sections which have a thickness of 40mm compared to 25mm thickness of the walkway sections.

Individual Components

Travel and Transport

It's clear to see from figure 28 that transport contributes to the most carbon emissions. Approximately 68.8% of the total carbon emissions from the trial at Newsham Park are from the Transport section.

Trial 1. Walkway (HMA surface)

- Section 1: This section uses HMA for both the surface and binder courses. Transport-related emissions total 85.5 kgCO_2e, representing 75.5% of the overall carbon emissions for this section.

- Section 2: This section uses an HMA surface with LJMU AC 20 HAN-CMA as the binder course. Transport emissions are 39.8 kgCO_2e, accounting for 66.5% of the total section emissions.

- Section 3: This section uses an HMA surface with LJMU AC 20 + 20% RAP HAN-CMA as the binder course. Transport emissions are 39.7 kgCO_2e, representing 66.7% of the total emissions. The slight increase in proportion is due to additional transport associated with RAP.

Trial 2. Walkway (LJMU HAN-CMA surface)

- Section 1: This section uses LJMU AC 6 HAN-CMA as the surface course with an AC 20 HMA binder course. Transport emissions total 62.6 kgCO_2e, representing 73.1% of the overall emissions.

- Section 2: This section uses LJMU AC 6 HAN-CMA as the surface course with LJMU AC 20 + 20% RAP HAN-CMA as the binder course. Transport emissions are 16.9 kgCO_2e, accounting for 52.7% of total emissions.

- Section 3: This section uses LJMU AC 6 HAN-CMA with 10% rubber crumb as the surface course and LJMU AC 20 HAN-CMA as the binder course. Transport emissions are 17.0 kgCO_2e, representing 52.5% of the total. The slight increase is likely due to transport impacts from sourcing rubber from Portugal; this could be reduced with a local supplier.

Trial 3. Cycle Path (HMA surface)

- Section 1: This section uses AC 10 HMA as the surface course over an AC 20 HMA binder course. Transport emissions total 94.7 kgCO_2e, representing 74.3%

of overall emissions.

- Section 2: This section uses AC 10 HMA as the surface course with LJMU AC 20 CMA as the binder course. Transport emissions are 53.0 kgCO_2e, accounting for 67.8% of the total.
- Section 3: This section uses AC 10 HMA as the surface course with AC 20 + 20% RAP as the binder course. Transport emissions increase to 56.8 kgCO_2e, representing 69.6% of total emissions. As noted previously, the use of RAP can increase transport-related emissions, with a rise of 2.1 kgCO_2e observed in this case.

Trial 4. Cycle Path (LJMU HAN-CMA surface),

- Section 1: This section uses LJMU AC 6 HAN-CMA as the surface course with an AC 20 HMA binder course. Transport emissions total 60.9 kgCO_2e, accounting for 70.1% of the total emissions.
- Section 2: This section uses LJMU AC 6 HAN-CMA as the surface course with LJMU AC 20 + 20% RAP HAN-CMA as the binder course. Transport emissions are 20.3 kgCO_2e, representing 52.8% of the total.

Transport is the dominant source of carbon emissions across all trial sections, consistently contributing around 52–76% of total emissions. While the use of CMA and RAP reduces overall carbon output, it does not significantly reduce the proportion attributed to transport. In some cases, particularly where RAP or rubber crumb are used, transport emissions increase due to longer haulage distances. These findings highlight that, alongside material selection, optimising logistics and sourcing materials locally is critical to achieving further carbon reductions.

Plant

The total plant-related emissions across the entire trial are approximately 92.0 kgCO_2e, accounting for 11.7% of the total carbon emissions at Newsham Park.

Trial 1. Walkway (HMA surface)

- Section 1: This section uses HMA for both the surface and binder courses. Plant-related emissions are 7.7 kgCO_2e, representing 10.8% of the total emissions for this section.

- Section 2: This section uses an HMA surface with LJMU AC 20 HAN-CMA as the binder course. Plant-related emissions are 7.6 kgCO_2e, representing 12.6% of total emissions. Emissions are lower than in Section 1 due to the HAN-CMA binder not requiring heating during production.

- Section 3: This section uses an HMA surface with LJMU AC 20 + 20% RAP HAN-CMA as the binder course. Plant-related emissions are also 7.6 kgCO_2e, representing 12.7% of total emissions. Sections 2 and 3 have identical plant emissions due to the same mixing and compaction processes being used.

Trial 2. Walkway (LJMU HAN-CMA surface)

- Section 1: This section uses LJMU AC 6 CMA as the surface course with an AC 20 HMA binder course. Plant-related emissions are 8.1 $kgCO_2e$, representing 9.5% of total emissions. These emissions are higher than in Trial 1, Section 2 due to increased material thickness (50 mm binder and 25 mm surface), requiring more aggregate heating.

- Section 2: This section uses LJMU AC 6 HAN-CMA as the surface course with LJMU AC 20 + 20% RAP HAN-CMA as the binder course. Plant-related emissions are 7.0 $kgCO_2e$, representing 21.9% of total emissions.

- Section 3: This section uses LJMU AC 6 HAN-CMA with 10% rubber crumb as the surface course and LJMU AC 20 HAN-CMA as the binder course. Plant-related emissions are 7.0 $kgCO_2e$, representing 21.7% of total emissions. Sections 2 and 3 have identical plant emissions due to the same construction processes. The slightly lower percentage in Section 3 is due to higher overall emissions from the transportation of the rubber crumb.

Trial 3. Cycle Path (HMA surface)

- Section 1: This section uses AC 10 HMA as the surface course over an AC 20 HMA binder course. Plant-related emissions are 10.4 $kgCO_2e$, representing 8.2% of total emissions. Emissions are higher than the walkway HMA baseline due to the increased surface course thickness.

- Section 2: This section uses AC 10 HMA as the surface course with LJMU AC 20 HAN-CMA as the binder course. Plant-related emissions are 9.3 $kgCO_2e$, representing 11.9% of total emissions.

- Section 3: This section uses AC 10 HMA as the surface course with AC 20 + 20% RAP as the binder course. Plant-related emissions are also 9.3 $kgCO_2e$, representing 12.3% of total emissions. As with previous comparisons, Sections 2 and 3 share identical plant emissions due to consistent construction methods. The slightly lower percentage is due to increased total emissions from RAP transport.

Trial 4. Cycle Path (LJMU HAN-CMA surface),

- Section 1: This section uses LJMU AC 6 CMA as the surface course with an AC 20 HMA binder course. Plant-related emissions are 9.5 $kgCO_2e$, representing 11.0% of total emissions.
- Section 2: This section uses LJMU AC 6 HAN-CMA as the surface course with LJMU AC 20 + 20% RAP HAN-CMA as the binder course. Plant-related emissions are 8.4 $kgCO_2e$, representing 21.9% of total emissions.

Plant-related emissions contribute a moderate proportion of total carbon emissions, approximately 7–22%. The use of HAN-CMA generally reduces plant emissions due to the elimination of heating requirements, particularly in binder courses. However, these savings are somewhat offset by the need for on-site mixing equipment when using HAN-CMA. While the same compaction equipment (e.g. whacker plates and rollers) is used for both CMA and HMA, meaning no reduction in emissions at this stage, the additional mixing requirement limits the overall CO_2 savings within the plant category. Furthermore, factors such as layer thickness and material composition can increase energy demand during production, reducing potential benefits. Where identical construction processes are used, plant emissions remain consistent across sections, with variations in percentage contribution largely driven by changes in total emissions from other sources, particularly for the transport of RAP and rubber crumb.

Material Components (Binder and Surface course, aggregate and recycling)

Figure 28 illustrates the carbon emissions associated with each material component across the trial sections, enabling comparison of carbon savings between different asphalt types. The sub-base aggregate remained constant throughout all sections, contributing 0.4 $kgCO_2e$ per section. Similarly, recycling impacts were consistent across all sections, with a value of 0.9 $kgCO_2e$.

Trial 1. Walkway (HMA surface)

- The surface material for all three sections is AC 6 HMA. As the same material is used throughout, emissions are identical at 6.75 $kgCO_2e$ per section.
- Section 1: The binder course is AC 20 HMA, with a carbon emission value of 11.8 $kgCO_2e$.
- Section 2: The binder course is LJMU AC 20 HAN-CMA, with emissions of 5.3 $kgCO_2e$. This represents a 55.1% reduction compared to the AC 20 HMA binder.
- Section 3: The binder course is LJMU AC 20 + 20% RAP HAN-CMA, with emissions of 5.0 $kgCO_2e$. This provides a further saving of 0.3 $kgCO_2e$ compared to the CMA binder without RAP, equating to a 57.6% reduction relative to the AC 20 HMA binder.

Trial 2. Walkway (LJMU HAN-CMA surface)

- The surface course for Sections 1 and 2 is LJMU AC 6 HAN-CMA, with emissions of 2.637 $kgCO_2e$. This represents a 60.9% reduction compared to the AC 6 HMA surface.
- The surface course for Section 3 is LJMU AC 6 + 10% rubber HAN-CMA, with emissions of 2.628 $kgCO_2e$. This shows a marginal improvement, equating to a 61.1% reduction compared to AC 6 HMA.

- The binder courses (AC 20 HMA, LJMU AC 20 HAN-CMA, and LJMU AC 20 + 20% RAP HAN-CMA) follow the same trends discussed in Trial 1, with CMA and RAP combinations delivering significant carbon savings over traditional HMA.

Trial 3. Cycle Path (HMA surface)

- The surface course for all sections is AC 10 HMA, with emissions of 10.05 kgCO$_2$e. This is higher than AC 6 HMA due to the increased layer thickness, resulting in greater material usage.
- As the binder materials remain consistent with those used in Trial 1, the same carbon emission trends and savings apply for the binder course in this trial.

Trial 4. Cycle Path (LJMU HAN-CMA surface)

- The surface course for both sections is LJMU AC 10 CMA, with emissions of 4.2 kgCO$_2$e. This is 1.6 kgCO$_2$e higher than LJMU AC 6 CMA due to increased thickness. However, it still represents a 58.4% reduction compared to AC 10 HMA.
- As with Trial 3, the binder materials remain consistent, and therefore the same carbon emission reductions observed in earlier trials apply.

Material production shows substantial potential for carbon reduction, particularly through the use of LJMU HAN-CMA in both surface and binder courses. LJMU HAN-CMA consistently delivers significant savings, between 55 and 62%, compared to traditional HMA, with additional marginal benefits achieved through the incorporation of RAP and rubber crumb. Surface course emissions are strongly influenced by layer thickness, with thicker applications resulting in higher emissions despite material efficiency improvements, found in the AC 10 results.

While sub-base aggregate and recycling contributions remain constant and relatively minor, the choice of asphalt material has a pronounced impact on total emissions. Overall, the results demonstrate that adopting HAN-CMA technologies for both surface and binder course layers, offers a highly effective strategy for reducing embodied carbon in road and pavement construction.

Conclusions: (HAN-CMA)

The carbon calculation results demonstrates that significant reductions in carbon emissions can be achieved through the adoption of the HAN-CMA technologies in place of traditional HMA. The findings show that HAN-CMA provides substantial carbon savings at both material and whole-section levels, particularly when applied to both surface and binder courses.

At the material level, HAN-CMA consistently achieves carbon reductions in the range of approximately 55 to 62% compared to equivalent HMA mixtures. The substitution of the binder course alone offers considerable benefits, highlighting this layer as a key opportunity for reducing embodied carbon. Additional savings can be achieved through the incorporation of RAP and rubber crumb; however, these benefits are highly dependent on transport distances and can be offset where haulage requirements are increased.

Despite the effectiveness of HAN-CMA in reducing material-related emissions, transport remains the dominant contributor to overall carbon impact, accounting for approximately 52 to 76% of total carbon emissions across all trial sections. This significantly limits the proportional reduction achievable through material substitution alone and emphasises the importance of optimising logistics and prioritising locally sourced materials.

Plant-related emissions represent a relatively small proportion of the total carbon emissions at approximately 7 to 22%. While the HAN-CMA reduces emissions by eliminating the need for heating, the requirement for on-site mixing, combined with the continued use of conventional compaction equipment, limits the extent of carbon savings within this stage of the process.

The results also demonstrate that pavement design plays a critical role in overall emissions. Increased layer thickness, as observed in the cycle path sections, leads to higher total carbon outputs due to increased material usage, regardless of the asphalt type used.

Overall, the study highlights that the most effective approach to reducing carbon emissions in pavement construction is a combined strategy. *The use of HAN-CMA in both surface and binder courses, alongside minimised transport distances and optimised pavement design, offers the greatest potential for achieving meaningful and sustainable carbon reductions.*

LJMU-Low Heat Asphalt (HAN-LHA) CO2 Emission Estimation – Based on Colas

The estimation of carbon emissions associated with the Low Heat Asphalt (HAN-LHA) presents a methodological challenge due to the absence of a directly defined emission factor for the heating of aggregates. In contrast to conventional asphalt production methods, the primary distinction between Cold Mix Asphalt (HAN-CMA) and HAN-LHA lies in the heating of aggregates mixtures to approximately 60°C prior to mixing.

As both HAN-CMA and HAN-LHA utilise identical constituent materials, it is assumed that emissions related to material production, transportation, and recycling processes remain unchanged. Consequently, any variation in total carbon emissions between HAN-CMA and HAN-LHA is attributed solely to plant-related processes, specifically the additional energy required for aggregate heating.

Since LHA was not implemented during the Newsham Park trial, no direct measurements of energy consumption were recorded. Therefore, an estimation approach has been adopted, whereby CMA sections are theoretically substituted with LHA, and emissions are scaled proportionally based on temperature differentials.

Equation, Methodology and Assumptions

To estimate the additional emissions associated with LHA, the following assumptions were made:

- Hot Mix Asphalt (HMA) production temperature: 160°C
- Ambient temperature: 20°C
- Temperature differential (HMA to HAN-CMA): 160°C-20°C=140°C
- Temperature differential (HAN-LHA to HAN-CMA): 60°C-20°C=40°C

The increase in emissions between HMA and CMA is used as a reference point and scaled proportionally to the HAN-LHA operating temperature (Δ40°C), as shown in Equation below:

$$\Delta \mathrm{CO}_2 e_{LHA} = \left(\frac{\Delta \mathrm{CO}_2 e_{HMA-CMA}}{140}\right) \times 40$$

Trial 1: Walkway with HMA Surface

The difference in emissions between HMA and HAN-CMA is 1.1 kgCO_2e (8.7 – 7.6). Applying the scaling approach:

$$(1.1/140) \times 40 = 0.314 \text{ kgCO}_2\text{e}$$

This results in an estimated increase of 0.314 kgCO_2e, giving a total plant-related emission of 7.914 kgCO_2e for the HAN-LHA binder with an HMA surface. This value is consistent across Sections 2 and 3 as HAN-CMA binder with and without RAP give the same total plant related emissions.

The total emissions for trial 1 section 2 would therefore be 61.014 kgCO_2e if HAN-LHA binder was used, resulting in emissions saving of 23.9% compared to HMA. This is a saving of 0.4% less than the saving from HAN-CMA.

The total emissions for trial 1 section 3 would be 60.714 kgCO_2e if LHA binder with RAP was used, resulting in emissions saving of 24.3% compared to HMA. This is a saving of 0.4% less than the saving from HAN-CMA.

Trial 2: Walkway with LHA Surface

Section 1

The emission difference is 0.6 kgCO_2e (8.7 – 8.1):

$$(0.6/140) \times 40 = 0.171 \text{ kgCO}_2\text{e}$$

This corresponds to an estimated increase of 0.17 kgCO_2e, resulting in total plant related emissions of 8.27 kgCO_2e.

The total estimated carbon emissions would be 69.77kgCO2e, resulting in a total carbon saving of 13% compared to HMA. This is a saving of 0.2% less than the saving from HAN-CMA.

Sections 2 and 3

The emission difference is 1.7 $kgCO_2e$ (8.7 – 7.0):

$$(1.7/140) \times 40 = 0.486\ kgCO_2e$$

This yields an estimated increase of 0.486 $kgCO_2e$, with total emissions of 7.49 $kgCO_2e$.

The total emissions for trial 2 section 2 would therefore be 50.286 $kgCO_2e$ if HAN-LHA binder was used, resulting in emissions saving of 37.3% compared to HMA. This is a saving of 0.6% less than the saving from HAN-CMA.

The total emissions for trial 2 section 3 would be 50.686 $kgCO_2e$ if HAN-LHA binder with RAP was used, resulting in emissions saving of 36.8% compared to HMA. This is a saving of 0.6% less than the saving from HAN-CMA.

Trial 3: Cycle Path with HMA Surface

The emission difference is 1.1 $kgCO_2e$ (10.4 – 9.3):

$$(1.1/140) \times 40 =0 .314\ kgCO_2e$$

Sections 2 and 3 both show an estimated increase of 0.314 $kgCO_2e$, resulting in total emissions of 9.614 $kgCO_2e$.

The total emissions for trial 2 section 2 would therefore be 74.414 $kgCO_2e$ if HAN-LHA binder was used, resulting in emissions saving of 22.2% compared to HMA. This is a saving of 0.4% less than the saving from HAN-CMA.

The total emissions for trial 2 section 3 would be 76.314 $kgCO_2e$ if LHA binder with RAP was used, resulting in emissions saving of 20.3% compared to HMA. This is a saving of 0.3% less than the saving from HAN-CMA.

Trial 4: Cycle Path with HAN-LHA Surface

Section 1

The emission difference is 0.9 $kgCO_2e$ (10.4 – 9.5):

$$(0.9/140) \times 40 = 0.257\ kgCO_2e$$

This produces an estimated increase of 0.257 kgCO$_2$e, with a total emission of 9.76 kgCO$_2$e.

The total estimated carbon emissions would be 77.657kgCO2e, resulting in a total carbon saving of 18.9% compared to HMA. This is a saving of 0.2% less than the saving from HAN-CMA.

Section 2

The emission difference is 2.0 kgCO$_2$e (10.4 – 8.4):

$$(2.0/140) \times 40 = 0.571\ \text{kgCO}_2\text{e}$$

This results in an estimated increase of 0.571 kgCO$_2$e, with total emissions estimated at 8.97 kgCO$_2$e.

The total estimated carbon emissions would be 60.271 kgCO2e, resulting in a total carbon saving of 37% compared to HMA. This is a saving of 0.6% less than the saving from HAN-CMA.

Summary: HAN-CMA & HAN-LHA

The analysis indicates that the implementation of HAN-LHA would result in a measurable but relatively modest increase in plant-related carbon emissions compared to HAN-CMA. This increase is directly attributable to the additional heating requirement of mixtures to 60°C.

Across all trials, using HAN-LHA binder results in consistent estimated carbon savings compared to HMA, although it performs slightly below HAN-CMA by around 0.2–0.6%. The increase in estimated plant-related emissions from adopting HAN-LHA is approximately 0.17–0.57 kgCO$_2$e, meaning overall reductions are still achieved. Overall, the results indicate that HAN-LHA binder is an effective low carbon alternative to HMA, especially in optimised section designs and when used alongside RAP.

Conclusion

ITSM Results

LJMU CMA Results

All Liverpool John Moores University Cold Mix Asphalt (LJMU HAN-CMA) mixtures, AC6, AC10, and AC20, achieved ITSM values after 3 days of curing that exceeded the minimum thresholds typically accepted by road engineers, namely 500 MPa, 1500 MPa, and 2500 MPa, respectively.

The LJMU HAN-CMA AC20 and HAN-CMA AC20 mixtures containing 20% RAP both achieved ITSM values exceeding 2500 MPa at 3 days of age. This indicates that the LJMU filler and emulsion significantly enhance the viscoelastic behaviour and adhesive internal mechanical properties of the cold mix asphalt.

7-Day ITSM Performance

All LJMU HAN-CMA AC6 mixtures demonstrated higher ITSM values at 7 days compared to conventional hot mix asphalt (HMA). This trend is consistent across AC10 HAN-CMA and AC20 HAN-CMA mixtures, both with and without RAP.

28-Day Performance (Conditioned and Unconditioned)

At 28 days, all LJMU HAN-CMA mixtures (both surface course and binder course), whether conditioned or unconditioned, exhibited superior ITSM results compared to HMA. This confirms the long-term mechanical performance advantages of LJMU HAN-CMA mixtures.

Effect of Rubber Content in HAN-CMA AC6

For HAN-CMA AC6 incorporating 10% fine rubber (by weight of dry aggregate materials), the ITSM values were recorded as follows:

These results indicate that AC6 HAN-CMA containing 10% rubber requires more than 3 days of curing before being suitable for use in walkways. Typically, a minimum ITSM value of 500 MPa is considered acceptable for walkway surfacing. While the 3-day strength falls below this threshold, the results at 7, 14, and 28 days exceed 500 MPa, demonstrating a progressive increase in stiffness with curing time.

Recommendations for Further Research

Further research is recommended to optimise the proportion of fine rubber crumb in AC6 HAN-CMA mixtures to achieve acceptable performance within 3 days or less. Suggested investigations include varying rubber content at 5%, 10%, 15%, and 20% of fine aggregates, or as a percentage of the emulsion binder content within the HAN-CMA mix.

LJMU HAN-LHA Results

The results demonstrate that LJMU HAN-LHA mixtures develop stiffness progressively with curing time, achieving and often exceeding the required ITSM targets after early curing stages. However, compared to HAN-CMA mixtures, HAN-LHA generally exhibits lower initial stiffness and slower strength development, particularly at early curing ages.

HAN-CMA mixtures consistently outperform HAN-LHA in both early-age and long-term stiffness across all mix types, AC6, AC10, and AC20, indicating superior curing efficiency and structural performance. Despite this, HAN-LHA mixtures show substantial stiffness gains over time, in some cases achieving comparable values after extended curing periods, highlighting their potential for long-term applications.

The inclusion of rubber in HAN-LHA mixtures tends to reduce stiffness and delay strength development, likely due to the swelling and ageing behaviour of rubber particles, which limits effective load transfer within the mixture. Similarly, the addition of RAP in HAN-LHA mixtures results in slower stiffness development, requiring longer curing periods to meet target performance levels.

Overall, LJMU HAN-LHA mixtures demonstrate good long-term performance potential, particularly where extended curing time can be accommodated. However, HAN-CMA mixtures remain superior in terms of early strength gain and overall stiffness performance, suggesting they are more suitable for applications requiring faster return to service

Wheel Tracking Rutting Test Results

LJMU CMA AC6

- The rutting curve for HAN-CMA AC6 remains nearly linear over most loading cycles, with rut depths generally less than 1 mm.
- HAN-CMA AC6 containing 10% rubber reached a maximum rut depth of 3.85 mm at 10,000 cycles, which is below the 4 mm limit recommended for roads carrying high traffic loads.

These results suggest acceptable rutting performance; however, optimisation of the rubber content is required. The findings indicate that the percentage of fine rubber dust should likely be reduced below 10% (by dry weight of aggregates) to further improve performance.

LJMU HAN-CMA AC10

The rutting curve remains almost linear between 2,000 and 10,000 load cycles, with rut depths typically less than 1 mm.
The maximum rut depth at 10,000 cycles is approximately 1 mm, well below the 4 mm recommended limit.

LJMU HAN-CMA AC20

- HAN-CMA AC20 without RAP shows a maximum value of 0.515 mm.

- HAN-CMA AC20 with 20% RAP recorded a maximum rut depth of 0.565 mm at 10,000 cycles.

Both mixtures are well below the 4 mm limit for heavily trafficked surface courses.

LJMU HAN-LHA AC6

Maximum rut depth of 0.745 mm, demonstrating better rut resistance than HAN-CMA AC6 of 0.89 mm.

The LJMU HAN-LHA AC 6 with 10% rubber has a maximum rut depth of 3.31 mm, outperforming LJMU AC6 with 20% rubber HAN-CMA with a maximum rut dept of 3.88 mm.

LJMU HAN-LHA AC10

Maximum rut depth of 0.6 mm, showing improved performance compared to HAN-CMA AC10 with a maximum rut depth of0.89 mm.

LJMU HAN-LHA AC20

Maximum rut depth of 0.4 mm, showing improved performance compared to HAN-CMA AC20 with a maximum rut depth of 0.515 mm.

Maximum rut depth with 20% RAP is 0.515 mm, showing improved performance compared to HAN-CMA AC20 with RAP with a maximum rut depth of 0.57 mm.

All mixtures tested HAN-CMA and HAN-LHA, demonstrate rutting performance well within the recommended 4 mm limit for high-traffic road applications. However, LJMU HAN-LHA mixtures consistently show slightly better rut resistance than their HAN-CMA counterparts. HAN-CMA mixtures still perform very well and offer a viable alternative to conventional HMA, although optimisation of rubber content, particularly in AC6, is recommended to further enhance performance.

4 Point Bending Test

Across all strain levels, the LJMU LHA samples consistently outperform their HAN-CMA counterparts, with the greatest benefits observed at higher strain levels (150 and 200 microstrain).

The addition of rubber crumb significantly enhances fatigue resistance, particularly under higher strain conditions, where it helps maintain substantially higher cycle lives. Among all mixtures tested, LJMU AC 6 + 10% rubber (HAN-LHA) shows the best overall performance, indicating superior durability and resistance to fatigue cracking.

The inclusion of 20% RAP generally reduces fatigue performance in HAN-CMA mixtures, although this effect is partially mitigated when produced as a HAN-LHA. Furthermore, comparison with conventional HMA mixtures highlights that all LJMU asphalt mixes provide improved fatigue resistance, confirming their suitability for applications requiring enhanced long-term pavement durability.

Overall, the results indicate that the combination of HAN-LHA and rubber modification offers the most effective approach for improving fatigue life, particularly in high-strain conditions.

Water Sensitivity Test

LJMU HAN-CMA Results

Overall, the results demonstrate that LJMU HAN-CMA mixtures exhibit superior resistance to water sensitivity compared to conventional HMA. For AC6, AC10, and AC20 mixtures, conditioning led to either a slight increase or maintenance of stiffness, in contrast to the consistent reduction observed in HMA samples. This behaviour is attributed to continued hydration processes within the HAN-CMA, which enhance internal bonding under conditioning.

However, the HAN-CMA AC6 mixture containing 10% rubber showed a notable reduction in stiffness after conditioning, indicating that higher rubber content may negatively affect moisture resistance. Despite this exception, the general trend confirms that LJMU HAN-CMA mixtures are well-suited for environments exposed to high moisture conditions, such as heavy rainfall or flooding, with performance advantages over traditional HMA

LJMU HAN-LHA Results

The results indicate that LJMU HAN-LHA mixtures generally exhibit slightly lower initial stiffness compared to the LJMU CMA counterparts, particularly in the AC6 mixtures. However, both LHA and HAN-CMA mixtures demonstrate similar moisture resistance, as reflected by comparable stiffness modulus ratios (SMR) and consistent stiffness gains after conditioning.

Notably, HAN-LHA mixtures show a more uniform and, in some cases, greater improvement in stiffness under water sensitivity conditioning, especially for AC20 and AC20 with RAP. The significant stiffness gain observed in the AC20 HAN-LHA with 20% RAP highlights its strong potential for use in moisture-prone environments.

In contrast to HAN-CMA, the inclusion of rubber in HAN-LHA AC6 does not negatively affect performance; instead, it leads to a substantial increase in stiffness after conditioning. This suggests that HAN-LHA mixtures may be more compatible with rubber modification under wet conditions.

Overall, LJMU HAN-LHA mixtures demonstrate good resistance to moisture damage and, despite slightly lower initial stiffness in some cases, provide reliable and in some instances enhanced performance under conditioning, making them a viable alternative to HAN-CMA and superior to conventional HMA in terms of water sensitivity.

Ageing ITSM Results

LJMU HAN-CMA Results

The results clearly demonstrate that LJMU HAN-CMA mixtures exhibit a significantly greater increase in stiffness after long-term ageing compared to conventional HMA. This is particularly evident in LJMU AC6 and LJMU AC10, where very high ageing indices indicate substantial strength development over time. The enhanced performance of the LJMU HAN-CMA is attributed to continued hydration and the formation of micro and macro crystalline structures within the asphalt mixtures, which contribute to increased stiffness and durability under elevated temperatures.

For the AC20 mixtures, both with and without 20% RAP, the results confirm that LJMU HAN-CMA continues to gain stiffness throughout its service life, outperforming HMA in terms of ageing. The presence of secondary cementitious materials plays a key role in this long-term strength development.

However, the inclusion of 10% rubber in LJMU AC6 HAN-CMA significantly limits stiffness gain during ageing, resulting in a much lower ageing index. This behaviour is likely due to the swelling and ageing of rubber particles, which reduces their ability to contribute to structural strength.

Overall, LJMU HAN-CMA mixtures demonstrate excellent long-term ageing performance, with substantially higher stiffness gains than HMA, confirming their potential as durable and sustainable alternatives for long-life pavement applications, although optimisation of rubber content remains necessary.

LJMU HAN-LHA Results

The results indicate that LJMU HAN-LHA mixtures experience significant stiffness gains after long-term ageing, with consistently higher ageing indices than their HAN-CMA counterparts in most cases. Although the initial unconditioned ITSM values of HAN-LHA mixtures are generally lower than those of CMA, the greater SMR values demonstrate a stronger relative improvement in stiffness over time.

This behaviour is likely influenced by residual moisture within the HAN-LHA mixtures, which may initially reduce stiffness due to rapid surface hardening during production. The ageing process allows this trapped moisture to evaporate, promoting further curing and resulting in substantial increases in stiffness.

For AC6 and AC10, HAN-LHA mixtures show particularly high ageing indices, indicating strong long-term performance potential. Unlike HAN-CMA, the inclusion of rubber in HAN-LHA mixtures does not significantly hinder stiffness development during ageing and results improved in ageing performance.

Overall, LJMU HAN-LHA mixtures demonstrate excellent long-term curing and ageing characteristics, with greater relative stiffness gains than HAN-CMA, despite lower initial stiffness. This highlights their potential as durable pavement materials, particularly where long-term performance and continued strength development are critical.

Air Void and Bulk Density Results

LJMU AC6 HAN-CMA produced an asphalt mixture with an air void content of 5.58%, which falls within the range typically accepted in practice. The AC6 HAN-LHA mixture showed a slight reduction in air voids to 4.86%.

The LJMU AC6 mixtures containing 10% rubber crumb exhibited significantly higher air void contents due to the elastic nature of the rubber, which reduces compaction efficiency. This resulted in air void contents of 14.79% for HAN-CMA and 15.67% for HAN-LHA.

The AC6 HMA mixture recorded an air void content of 8.64%, which is relatively high but may still be acceptable to road engineers depending on application.

For AC10 mixtures, the average air void content was 5.76% for LJMU HAN-CMA and 8.32% for HMA, both within acceptable limits. However, the LHA mixture showed a higher air void content of 7.14%, which may indicate reduced compaction efficiency, despite expectations of lower voids.

LJMU AC20 HAN-CMA mixtures with and without 20% RAP produced air void contents of 7.23% and 9.26%, respectively, which are close to the preferred range for binder course mixtures. The AC20 HAN-LHA mixture showed a lower air void content of 6.25%, indicating improved compaction.

The slightly elevated air void content in LJMU AC20 with 20% RAP is attributed to increased resistance to compaction and the presence of agglomerated RAP particles. This issue could be mitigated by further processing the RAP to achieve a particle size distribution similar to that of the virgin aggregates. The air void contents for AC20 with 20% RAP were 9.26% for HAN-CMA and 8.67% for HAN-LHA.

Leachate of Heavy Metals

The environmental analysis of the LJMU filler used in LJMU HAN-CMA and HAN-LHA mixtures indicates no adverse environmental impacts. The concentrations of heavy metals in the LJMU filler specimens were found to be below the regulatory limits for hazardous materials, confirming compliance with minimum environmental requirements. Furthermore, the bitumen emulsion and associated hydration processes act as effective stabilisation and solidification mechanisms for heavy metals, thereby limiting their mobility. As a result, any potential leachate is unlikely to pose a risk to groundwater or surface water resources.

The Volumetric Patch Test

The volumetric patch test results show that sections with HMA surface courses consistently achieve macrotexture depths that meet UK specification requirements, indicating good surface performance in terms of drainage and skid resistance. In contrast, the LJMU HAN-CMA surface courses produced lower macrotexture values, with some results falling below the minimum required threshold of 0.6 mm.

This reduced texture depth is likely influenced by the application of a seal coat, which may have filled surface voids and limited macrotexture. While HAN-CMA mixtures demonstrate potential, their surface characteristics require optimisation to meet specification standards. Further refinement of the seal coat application and surface finishing methods, along with continued monitoring under traffic, is recommended to improve macrotexture performance over time.

Pendulum Skid Resistance

The skid resistance results indicate that all sections with HMA surface courses consistently achieved high Pendulum Test Values (PTV), exceeding recommended thresholds for all road categories. This demonstrates excellent initial skid resistance and strong frictional performance.

In comparison, HAN-CMA surface courses exhibited lower initial skid resistance, with some values falling close to or below minimum recommended levels. However, an improvement in PTV was observed over time, suggesting that trafficking and environmental exposure contribute to the gradual development of surface micro texture. The application of a seal coat on the HAN-CMA sections is likely to have reduced initial skid resistance by masking aggregate texture.

Overall, while HAN-CMA surfaces show the potential to reach acceptable skid resistance levels with time, HMA surface courses provide superior immediate performance. Optimisation of HAN-CMA surface treatment, particularly the seal coat application, is recommended to enhance early-life skid resistance.

ITSM of cored samples from Newsham Park Trials

The ITSM results from the cored samples indicate variability in in-situ stiffness performance across the different mixtures. In general, HAN-CMA mixtures outperformed their HMA counterparts, with LJMU AC10 HAN-CMA and AC20 HAN-CMA exceeding the target stiffness requirements and demonstrating higher modulus values than the corresponding HMA mixes.

Conversely, the AC10 HMA failed to meet the minimum target stiffness, and although AC20 HMA met the required threshold, its performance was notably lower than laboratory-produced samples. The AC20 HAN-CMA with 20% RAP also fell below the target value, suggesting that the inclusion of RAP may reduce in-situ stiffness if not properly optimised.

The discrepancies between laboratory and field results are likely influenced by factors such as compaction quality, environmental exposure, and sample disturbance during coring. Overall, while HAN-CMA mixtures show strong potential for superior in-situ stiffness performance, careful attention to construction practices and material optimisation is essential to achieve consistent results in the field.

Air void and Bulk Density of cored samples from Newsham Park Trials

The results indicate that all cored samples exhibited lower bulk densities and higher air void contents compared to those produced under controlled laboratory conditions. This trend is consistent across both HMA and HAN-CMA mixtures and highlights the impact of field conditions on compaction quality.

HAN-CMA mixtures, in particular, showed lower densities and higher void contents, suggesting greater sensitivity to compaction during construction. In contrast, mixtures containing 20% RAP produced results closer to laboratory values, indicating more consistent field performance.

Overall, the findings suggest that reduced compaction efficiency on site is the primary cause of increased air voids and lower densities. This emphasises the importance of optimising construction practices and compaction methods to ensure that in-situ performance aligns more closely with laboratory expectations.

Recommendations

1. The LJMU Lead academic Professor Hassan Al Nageim and his research team recommended that all the trial sections reported in this report should be left in place for further visual inspections for a period of 24 and 36 months and more. LJMU Leading Academic Principal investigator over the coming 12 months will monitor the trial sections visually at every six months to provide and update the consortium with the necessary information. This is value for money and will help the industry to have a better insight on the performance of both the LJMU HAN-CMA & HAN-LHA Asphalt.

2. A further comprehensive 18 -24 months R&D study for further upgrading the durability properties of both HAN-CMA & HAN-LHA supported by trials in-real traffics road-sections to accommodate with a suitable dimensions for LJMU HAN-CMA & HAN-LHA of at least 1m x 9m similar to those tested in Newsham Park Trials need to be constructed to include the following;

   a) Conventional HMA AC 6, AC 10 and AC14 on LJMU AC 20 HAN-CMA binder course and similar regime of testing in this project should be applied for a period from 0-5 years to check the materials suitability for use in roads construction, car park pavement, walkways, road reinstatements and in-city – street pavements.

b) Conventional HMA AC 6, AC 10 and AC14 on LJMU AC 20 HAN-LHA binder course and similar regime of testing in this project should be applied for a period from 0-5 years to check the materials suitability for use in roads construction, car park pavement, walkways, road reinstatements and in-city – street pavements.

c) Extend this R&D project to modify further the emulsion using new technology esteemed out this project by LJMU research team at LJMU for producing further high quality emulsion with other environmentally friendly biomass and organic additive for producing and for the first time worldwide a high-resilient quality HAN-CMA and HAN-LHA with ability to pull out and store CO2 from atmosphere. The LJMU team has the capacity for producing such smart and very cheap mixtures.

3. Further development is required in order to develop the AC 6 with less than or 10% rubber to enhance the mechanical and durable properties to meet the required standard of road engineers in the UK.

Acknowledgments

Professor Hassan Al Nageim lead of LJMU Pavement Engineering Research Team extends his heartfelt gratitude to ADEPT Live Labs 2 and Liverpool council for providing the funds necessary that resulting in the outstanding achievement detailed in this report. Also unlimited thanks go to our colleagues,

- Pamela McGuinness, Commissioning & Project Delivery, Transportation and Highways I Liverpool City Council
- Krishna Priya SIVAPRASAD, Assistant Project Manager (Colas Ltd)
- Kira Jefferies, Carbon Analyst, Colas ltd
- Morgan Lloyd-Sanderson, the Project Development Engineer for his outstanding efforts and excellent projects outcomes.

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