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A laboratory study on cold-mix, cold-lay emulsion mixtures

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This paper describes laboratory experiments and presents results for the performances of cold-mix, cold-lay emulsion mixtures. The main objective of the experiments was to evaluate and improve the properties of the cold mixtures. The mixture properties evaluated were: volumetric properties, indirect tensile stiffness modulus (ITSM), repeated load axial creep and fatigue. These properties were compared with conventional hot asphalt mixtures not containing any waste/recycled materials. To optimise the performances of the mixtures, a target of ITSM value of 2000 MPa was selected. At full curing conditions, the stiffness of the cold mixes was found to be very similar to that of hot mixtures of the same penetration grade base bitumen (100 pen). Test results also show that the addition of 1–2% cement significantly improved the mechanical performance of the mixes and significantly accelerated their strength gain. The fatigue behaviour of the cold mixes that incorporated cement was comparable with that of the hot mixtures.

1. INTRODUCTION

Until now, cold mixes have been considered inferior to hot asphalt mixtures. There are three main concerns

(*a*) high air-void content of the compacted mixtures
(*b*) weak early life strength (caused mainly by the trapped water)
(*c*) the long curing times (evaporation of water/volatiles content and setting of the emulsion) required to achieve maximum performance.

Studies by Chevron Research Company in California concluded that full curing of cold bituminous mixtures on site may occur between 2 and 24 months depending on the weather conditions.[1]

In the UK, the publication of *Specification for Reinstatement of Openings in Highways*[2] by the Highway Authority and Utility Committee (HAUC) in 1992 helped to draw attention to cold-mix, cold-lay materials (cold mixes). The report allows the use of permanent cold-lay surfacing materials as an alternative to hot-mix asphalts for reinstatement work on low-volume roads and footways. A principal requirement is that these mixes perform adequately for a guaranteed period of 2 years, which has proved a challenge.[1]

In general, cold mixes are simple to produce and suitable for low-to-medium traffic conditions, work in remote areas and for small-scale jobs (at numerous locations) such as reinstatement work. However, currently there is no 'universally accepted' mix design method. Furthermore, due to a lack of uniformity in the laboratory procedures for cold-mix curing and evaluation of mechanical properties, in particular at an early age, it is difficult to form reliable correlations between the experimental results reported in the literature by different researchers.

The cold-mix samples were produced using a simplified (more practical) method previously proposed by the authors.[3,4] This paper presents an investigation into the volumetric properties and mechanical performance of the cold mixes, the effect of storage time on loose cold mixes, and a realistic evaluation of the rate of strength gain of cold mixes cured outdoors. For this investigation, the target compacted mix air void content was 5–10%. This air voids target is consistent with the most recent amendment to the HAUC document, which requires that the air voids after compaction of cold mixes used for carriageways is between 2 and 10%. It also agrees with guidance provided within the MPW-RI specification.[5] A target minimum indirect tensile stiffness modulus (ITSM) of 2000 MPa was also a requirement.[2,6]

The investigation used carboniferous limestone as the coarse aggregate. This is widely available in the UK. A by-product of red porphyry stone crushing was used as the fine aggregate.

This red porphyry sand (RPS) is produced during the production of decorative red-coloured coarse aggregates that are commonly used for chipping applications. The RPS availability fluctuates depending on the demand for the coloured coarse aggregates. Currently RPS is mainly used as fill material and for sub-grade formation.

Fly ash was used as a filler material. Traditionally, fly ashes have been used in a range of applications, namely as fill materials, for grouting, and soil stabilisation. Fly ash has also been used in road pavements as road bases, sub-bases and for sub-grade formation.[7]

From a pavement engineering perspective, the most useful types of mixtures that utilise fly ash for road pavements are fly ash-bound mixtures and granular fly ashes. These mixtures rely on the pozzolanic properties of the fly ash, which can harden in the presence of water and lime and/or cement. Fly ash is also used in cement-bound mixtures (building blocks, concrete, etc.).[7]

Fly ash has also been used as a replacement for conventional limestone fillers in hot rolled asphalts.[8] As fly ash particles tend to be more spherical in shape when compared with limestone, laboratory investigations have shown that fly ashes can enhance the workability of the bituminous mixtures, which is of great benefit particularly during the compaction process. Based on the laboratory results and as part of a resurfacing programme on the A689, UK in April 1991, a full-scale 320 m length trial section consisting of several hot-rolled asphalt segments containing pulverised fly ash filler was laid and compacted. Subsequently, the road sections were continuously monitored for any signs of distress over a period of 5 years and all trial sections were shown to perform [as expected] adequately.[8] Based on the success of the project, a publication was issued by the energy efficiency office of the Department of the Environment, on Future Practice (R&D profile 52) carrying the title *The Use of Pulverised Fuel Ash as a Bituminous Filler*.[9]

Material	Density: g/cm^3	Water abs.: %	Usage
Limestone	2·65	1·0	Coarse aggregate
Crushed glass	2·51	<0·5	Coarse and fine aggregate
Red porphyry sand*	2·59	0·9	Fine aggregate
Fine asphalt sand	2·66	0·8	Fine aggregate
Fly ash (Eggborough PS)†	2·20	–	Filler

* By-product of aggregate crushing. † PS, power station.

Table 1. Materials used for the cold mixes

The utilisation of fly ash in the UK has remained stable for a number of years (at around 50% of production). The amount of fly ash available in stock, in addition to fresh production is estimated to have remained relatively constant at about 250 000 000 t for a number of years.[7]

The mixtures also incorporated crushed glass. In the UK, the glass manufacturing sector attempts to operate a closed-loop recycling system; however, it has a limited capacity to accept green and mixed colour glass. As glass collection increases (to meet the 2006 packaging targets of 60%)[10] an 'excess' (300 000–400 000 t) of green glass is likely, for which alternative high-value, high-volume markets are required.

The incorporation of crushed glass, in particular green/mixed glass into bituminous mixtures is not new. Glasphalt hot mixtures incorporating 30% crushed glass (using a 100 pen. bitumen), laid at a trial site in Milton Keynes by RMC Aggregates Ltd. showed an average ITSM value of 1900 MPa. Meanwhile, in the same trial, the control hot mixture (not containing crushed glass) gave 2200 MPa. The average air-void contents for the Glasphalt and the control mixtures on that trial were 4·9 and 4·7%, respectively.[11]

2. AGGREGATE GRADATIONS FOR THE MIXTURES

The aggregate gradations of all the design mixtures used in this investigation were based on a modified Fuller's curve using a formula proposed by Cooper *et al.*[12] as shown below:

$$P = \frac{(100 - F)(d^n - 0{\cdot}075^n)}{D^n - 0{\cdot}075^n} + F \quad (1)$$

where P is the percentage of material passing sieve size d (mm); D is the maximum aggregate size (mm); F is the percentage filler; and n is an exponential value that dictates the concavity of the gradation line. The value used for n was 0·45, which provided good aggregate packing. A value of 4% was selected for F, which satisfied the allowable limits for filler content in dense bitumen macadams.[13]

3. MATERIALS USED

The constituent materials used for the cold mixes and their properties are given in Table 1.

The binder used was a cationic bitumen emulsion (60% bitumen content) with 100 pen. grade base bitumen obtained from Nynas Bitumens. The specific gravity of the base bitumen was 1·02. The maximum aggregate size selected for all the cold mixes was 12 mm. The gradation of the cold mixes is plotted in Figure 1. This gradation is within the limits recommended by the American Asphalt Institute.[14] The optimum residual bitumen content of the cold mix was previously designed at 6%.

4. MIXTURE DESIGNATION

Depending on the material types incorporated, the cold mixes were designated as shown in Table 2.

The coarse aggregates for all mixtures were composed of the following fractions (12–10 mm), (10–5 mm), (5–2·36 mm), and the fine aggregates were of particle sizes (2·36–0·075 mm). All filler material passed 0·075 mm.

As shown in Table 2, three types of cold mix were produced. Initially cold-mix-0 mixtures were made, but it was found that some aggregate particles of the cold-mix-0 mixtures were not fully coated with the bitumen emulsion. Although cationic bitumen emulsion was recommended to be compatible with most aggregates,[1] this was certainly found not to be the case

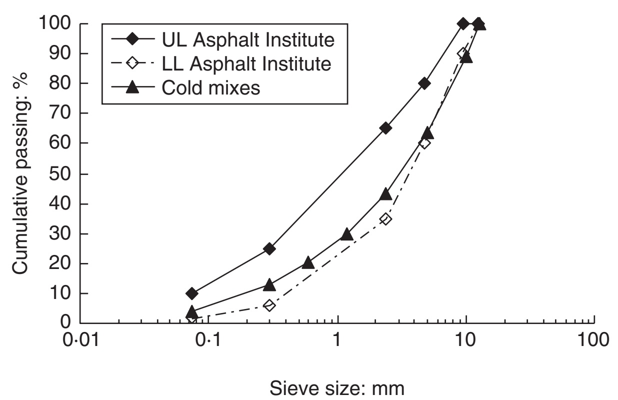

Figure 1. Aggregate gradation of the cold mixes compared with the American Asphalt Institute gradation:[14] UL, upper limit; LL, lower limit

Mixture type	Coarse aggregates (56·6%)	Fine aggregates (39·4%)	Filler (4%)
Cold mix-0	Limestone	Red porphyry sand	Fly ash
Cold mix-1	Limestone	60% red porphyry sand 40% quartzite sand	Fly ash
Cold mix-2	68% limestone 32% crushed glass	70% Quartzite sand 30% crushed glass	Fly ash

Table 2. Mixture designation and composition of the cold mix

with the RPS used in this investigation. This has been previously explained as a result of the affinity between bitumen emulsion and aggregates, which can be affected by the surface charges of the materials.[1]

In order to improve the degree of coating in the cold-mix-1 mixtures, the fine aggregates portion (as shown in Table 2) were made up of a combination of a maximum of 60% RPS and 40% quartzite sand. This composition was based on coating test trials.

Cold mix-2 incorporated 30% crushed glass by weight of total aggregates and was composed of 60% 5–2·36 mm particles and 40% passing 2·36 mm. This was based on the availability of the crushed glass particle sizes. Replacement levels of up to 30% by mass of aggregates in hot mixtures (Glasphalt) have already been successfully tested in full-scale trials in the UK with encouraging performance results.[11] The performance of Glasphalt was also compared with that of cold mix-2.

In cases where an accelerated rate of strength gain was required, 1 to 2% cement by mass was added to the mix to accelerate the curing process. Rapid-setting cement was found to further accelerate the rate of strength gain.[15]

5. MIXTURE PRODUCTION AND MECHANICAL PROPERTIES TESTED

Currently, there is no universally accepted design mixture for a cold mix. In this investigation the mixtures were produced using a simplified cold-mix design procedure developed previously by the authors.[3,4] This design procedure overcomes the impractical requirement to determine the optimum water content at the compaction on site. It ensures that the air void requirement is met; that the retained stability is evaluated at optimum residual bitumen content only, which reduces the number of samples needed, and it also provides data on the ultimate strength of the cold mix under full curing conditions.

The mix design procedure involves a number of sequential steps which are as follows

(*a*) determination of aggregate gradation
(*b*) estimation of initial emulsion content
(*c*) binder coating tests with variations in pre-wetting water content to obtain the best aggregate coating
(*d*) determination of adequate compaction level to satisfy final air-void requirements
(*e*) variation of emulsion content
(*f*) curing of compacted specimens
(*g*) determination of optimum residual bitumen content
(*h*) determination of retained stability at optimum residual bitumen content
(*j*) determination of ultimate strength at full curing conditions.

In summary, the mixing process was carried out as follows: 3600 g of aggregate material, which had been proportioned, were prepared (for three samples). The aggregates were dry mixed, then combined with the required pre-wetting water to produce an 'even' mix. The required bitumen emulsion was then added to the aggregates and mixed until a satisfactory coating was obtained. Before compaction the mixture was neither too 'sloppy' nor too stiff. Air drying may be needed if the mixture becomes too 'sloppy'.

Compaction of the cold mix specimens was carried out using a Gyropac[16] compactor set at 240 kPa axial pressure (for 100 mm diameter samples) with an angle of gyration of 2°. Two compaction levels are routinely used with this type of equipment.

(*a*) Medium compaction level: 80 revolutions in the Gyropac, which is equivalent to the compaction effort generated when applying 50 blows to each end of the sample using a Marshall hammer.
(*b*) Heavy compaction level: 120 revolutions in the Gyropac, which is equivalent to the compaction effort generated when applying 75 blows to each end using a Marshall hammer.

Following several compaction trials with the Gyropac, it was found that in order to achieve the target air-void content of 5–10% the compaction level had to be increased by up to twice the 'heavy' compaction level routinely specified. This higher compaction level was subsequently referred to as 'extra heavy compaction'.

Laboratory curing of the cold mix was carried out in an oven set at 40°C. Full curing conditions were achieved when the specimens, following repeated weighing, maintained a constant mass at 40°C. Typically, full curing conditions were achieved within 18–21 days for samples with air void values in the range 8–9%.[15]

The mechanical properties tested were: ITSM[17] at 20°C, dynamic creep at 40°C and fatigue at 20°C.[18] A universal materials testing apparatus (MATTA) was used for these tests.

6. ITSM COMPARISON OF THE COLD MIX TO HOT MIXTURES (100 PEN. GRADE)

Details of the ITSM tests are shown in Figure 2. The ITSM of the various cold mixtures were compared with hot mixtures produced with the same 6% bitumen content. The bitumen was

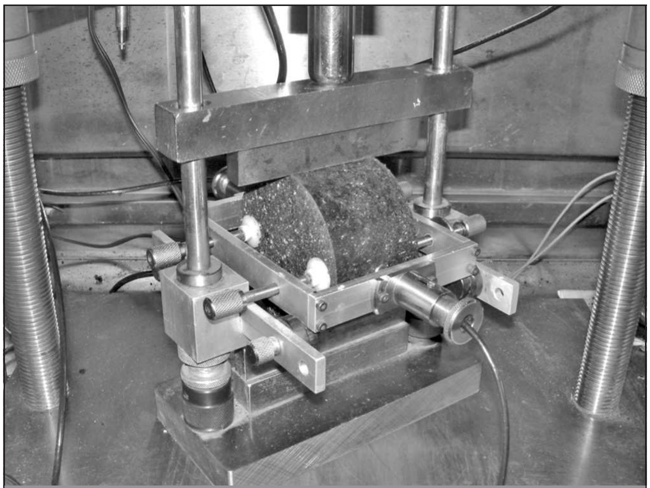

Figure 2. ITSM test configuration

an equivalent grade to the base bitumen used for the emulsion (that is, 100 pen.). Two hot mixtures were produced from limestone coarse aggregate, fine quartzite sand and fly ash filler. The mixes were graded identically, however, the mixing and compaction temperatures were set at 140 and 125°C, respectively.[19] The mixtures were compacted using a Gyropac compactor. One of the mixtures was compacted using a medium compaction effort, whereas the other hot mix was compacted using heavy compaction. The properties of the mixtures are given in Table 3.

Referring to Table 3, in order to meet the target air void range of 5 to 10%, the cold mix was compacted twice at the heavy compaction level. Even subjected to this degree of compaction, air void values in the range of 8 to 9% could only be achieved.

It is well known that high air void content is an inherent problem of cold mixes.[1] This is because the bitumen emulsion partially sets during compaction at the ambient temperatures. This causes the mixture to stiffen and leads to higher amounts of air voids when compared with hot mixtures.

The need for a heavier compaction level for cold mixes is well known within the highways industry.[1] These tests were laboratory tests in which the application of a heavy compaction level using the Gyropac was easily achievable. On site, heavier compaction efforts can be achieved using a heavier road roller and a greater number of 'passings'; however, this raises issues of efficiency. Furthermore, over-compaction of the lower pavement layers needs to be carefully monitored. Nonetheless, successful cold mix site trials have been achieved.[20] The successful introduction of cold mixes into practice also depends on the manufacturer of the bitumen emulsion. The pavement industry requires a bitumen emulsion with improved workability allowing the mixtures to be compacted at lower compaction levels. This is not beyond the capability of the manufacturers.

Mixture type	Compaction effort	Air voids: %	ITSM: MPa
Cold mix-0	2 × heavy	9·7	1680
Cold mix-0 + 2% RSC	2 × heavy	9·6	2500
Cold mix-1	2 × heavy	9·6	2276
Cold mix-1 + 1% RSC	2 × heavy	9·3	3378
Cold mix-1 + 2% RSC	2 × heavy	9·2	4973
Cold mix-2	2 × heavy	8·4	2275
Cold mix-2 + 1% RSC	2 × heavy	8·6	3290
Cold mix-2 + 2% RSC	2 × heavy	8·8	4339
100 pen. hot mix	Medium compaction	4·7	2161
100 pen. hot mix	Heavy compaction	3·4	2525

RSC, rapid setting cement.

Table 3. Properties of the cold mix compared to hot mixes with same binder grade (100 pen.)

Laboratory experiments which prepared the test samples in two thin layers of cold mix have previously been carried out by the authors. The second layer was applied after the first layer had undergone some degree of curing. A priming coat was applied to the surface of the first thin layer, before applying the second layer. It was found that the performance of these layered samples was satisfactory.[15] The application of thinner double layers on site would require less compaction.

Full curing conditions (in an oven set at 40°C) were achieved after 18–21 days. The stiffness of most of the cold mix specimens, subjected to full curing conditions, did meet the minimum stiffness target of 2000 MPa, with the exception of cold mix-0. This was thought to be due to reduced coating achieved in this mix as explained in Section 4. Cold mix-1 and cold mix-2 gave better coating than cold mix-0 and hence gave higher ITSM values. The addition of 1 to 2% cement significantly increased the ITSM values.

The air void of cold mix-2 (incorporating 30% crushed glass) was slightly lower than that of cold mix-1. This is because crushed glass offers less friction during compaction. These results are comparable with the results obtained from hot Glasphalt mixtures[11] mentioned earlier.

The results shown in Table 3 also show that the air voids of cold mix-2 was somewhat higher than the Glasphalt hot mixtures. On the other hand, the ITSM values of cold mix with 30% crushed glass at full curing were comparable (somewhat stiffer) than Glasphalt, even without the incorporation of cement. Due to its amorphous nature and its high silica content, when finely ground, glass possesses pozzolanic properties.[20] The crushed glass used within this investigation contained about 0·85% passing 0·075 mm (filler fraction). This might have contributed to the improved strength of the cold mix incorporating crushed glass.

In comparison with cold mixes, hot bituminous mixtures [when] mixed and compacted at the correct temperatures normally possess better coating and workability properties as well as lower air void values at lower compaction efforts. This is evident from the air voids and compaction effort results shown in Table 3.

When cold mixes were brought to full curing condition by oven drying at 40°C for 18–21 days (until achieving a constant weight), the samples should have undergone some level of oxidation, hence stiffening the bitumen.[15]

7. EFFECT OF STORAGE TIME ON COLD MIXES

This part of the investigation was to evaluate the effect of storage time of the loose cold mix following mixing and prior to compaction. The length of storage time required is a variable and depends on the scale of the proposed works. In practice, it is important to be able to store loose cold mix for small-scale works, such as road maintenance operations performed at various locations along a section of road.

It has been mentioned in the previous section that the performance of cold mix is influenced by the 'affinity' between the aggregate and the bitumen emulsion.[1] This was the case with the cold mix-0 mixtures (Table 2) that were used for this particular experiment. A slightly lower ITSM value was therefore recorded (Table 3) due to the reduction in coating.

The cold-mix, wet-loose mixtures were stored (following mixing with the emulsion and after lightly air drying the mixture to avoid clumping) in a sealed container for 0, 3, 6, 24, and 48 h before compaction. The compacted samples were then fully cured in an oven at 40°C (until a constant mass was achieved). Two types of mixtures were tested: mixtures without cement and mixtures with 2% rapid setting cement (RSC). Test results of air voids and ITSM values at 20°C of the fully cured compacted samples are presented in Figures 3 and 4. As the loose mixtures were lightly air dried before they were stored in a sealed container, very little water was squeezed out during the compaction process.

Figure 3 illustrates that as the mixtures became stiffer (and therefore less workable) during compaction in line with storage time, there was an increase in air voids. Cold mix-0 containing RSC was less workable than without RSC. This was indicated by an increase in air void content.

As the emulsion sets with increasing curing time, this leads to an increase in compacted air voids with increased storage time. Cold mix-0 + 2% RSC had a larger number of air voids than the loose mixture for the entire storage duration with a smaller difference recorded within the first 6 h. These higher values are due to the hydration of cement in the presence of moisture. This causes the loose mixture to be somewhat stiffer and less workable during compaction when compared with the mixture without cement.

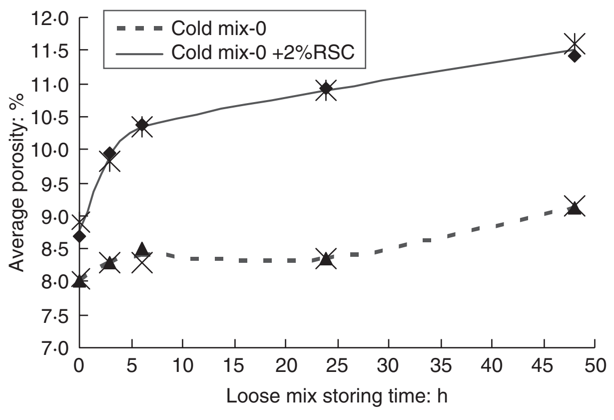

Figure 3. Air voids of fully cured compacted CBEM-0 plotted against loose mixture storage time

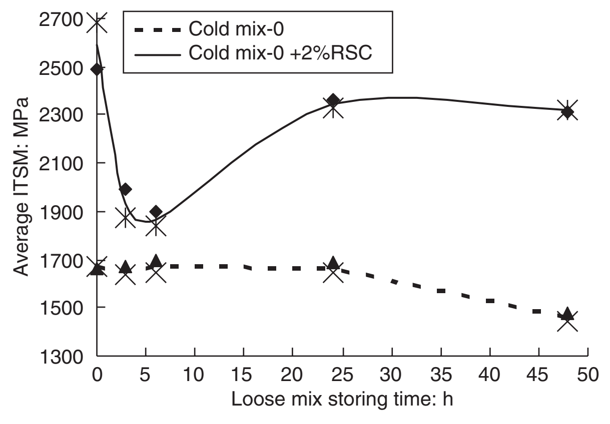

Figure 4. ITSM of fully cured compacted cold mix-0 plotted against loose mixture storage time

Figure 4 shows that the ITSM values of cold-mix-0 mixture (fully cured with no cement) remain relatively unchanged up to 24 h storage time with a very gradual reduction beyond 1 day storage. The ITSM values of the fully cured cold mix-0 + 2% RSC on the other hand were overall greater than the mixture without cement at all storage times. However, there was a very noticeable reduction in ITSM values within the 3 and 6 h loose mixture storage times.

It is interesting to note that the highest ITSM value for the mixture with cement was obtained when the wet mixture was compacted immediately following the mixing process (time 0 h). This matter was not fully investigated; however, it is discussed below.

The results suggest that when the mixtures were compacted within a very short time of the cement being added, the cement hydration products would have been allowed to form in the available spaces between the mineral aggregates and hence the hydration products act as bonds between the aggregate particles. Simultaneously, they form wedges of hydrated cement-fines mortar which lock the aggregate skeleton in place.

Due to hydration, the crystalline cementitious products form mainly in the first 6 h. Therefore, any delay in compaction from (time 0) will allow more hydration products to form in the loose wet mixture. This delayed compaction during the first few hours (up to 6 h in this case) would have caused damage to these relatively weak crystalline formations, which results in a reduction in bond between the mineral aggregate particles and hence lower ultimate ITSM. (It is similar to having increased the fine aggregate content of the mixture.)

After the 24 and 48 h loose mixture storage times, the majority of the cement hydration process would have taken place and the cementitious mortar formed would have become hard or tough enough so that any damage to the bonds between the crystalline phase and the mineral aggregates during compaction should have greatly reduced. As the hardened cement phase occurs (as irregularly shaped wedges) in the interstices between the larger mineral aggregate particles, it is logical that when these mortar wedges were partially broken into medium-sized particles, the increased roughness of the mixture (which was evident from the increased specimen air voids) provides an improvement in the

Figure 5. Outdoor curing of cold-mix samples

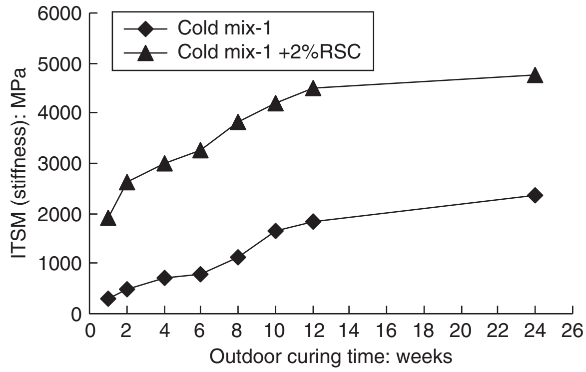

Figure 6. Rate of strength gain of cold-mix samples cured outdoors

aggregate interlock. Furthermore, the higher angle of internal friction that is present in these mixes due to the hydrated cement particles results in greater values of ITSM.

8. OUTDOOR CURING OF THE COLD MIXES

Samples of cold mix-1 mixes, without and with 2% RSC were manufactured and cured under 'out-door exposure conditions' (full exposure to rain and actual temperature profiles) in order to better simulate on-site conditions. This was carried out to evaluate the mixtures' realistic 'rate of strength gain' with time. Following compaction, the samples were kept in their moulds for 24 h at 24°C room temperature prior to extrusion. The sides of the samples were then sealed with plastic adhesive tape and placed on a flat metallic surface outdoors (on the roof of the school of civil engineering building, University of Leeds), as shown in Figure 5. The objective of this treatment was to simulate realistic site curing conditions where the evaporation of water will predominantly occur through the surface of the mixture.

Outdoor curing began in February 2002, with an average outdoor temperature of 10°C. Rain, which was a very frequent occurrence during the specimens' curing period, resulted in a slight wear of the surfaces of the samples. However, the samples remained intact and in good shape. At regular intervals, two samples were selected for testing. Contrary to British Standard recommendations, each sample was tested for ITSM at 20°C only once, in order to avoid damage (as had been experienced) when a sample was subsequently tested at a later age. The samples were tested at ages: 1, 2, 4, 6, 8, 10, 12 and 24 weeks. The rate of strength gain (in terms of ITSM at 20°C) of the samples is shown in Figure 6.

With respect to outdoor curing, samples with no added cement gained strength slowly with time (as shown in Figure 6). The ITSM target of 2000 MPa[2,6] was only achieved after an estimated 16 weeks of outdoor curing. On the other hand, samples with 2% RSC showed greatly improved performance, as they required less than 2 weeks of curing to meet the ITSM target of 2000 MPa. Stiffness values were not tested beyond 24 weeks (6 months), but the trend shown in Figure 6 does indicate a much more gradual but continued gain in stiffness. In either case, the rate of gain of strength was 'relatively' fast when compared with some cold mix site trials without cement which required much longer curing times of 2 to 24 months.[1] Direct comparison with other full-scale cold mix surfacing investigations was not possible as the mixtures in the field were influenced by various factors, including; compaction level, climatic conditions: rainfall, surface drainage, traffic conditions, etc.

9. CREEP PERFORMANCE

Dynamic creep tests were carried out using a universal material testing apparatus (MATTA) as shown in Figure 7 (a typical configuration for illustration), and was set at the following test conditions

(*a*) pulse width, 1000 ms
(*b*) pulse period, 2000 ms
(*c*) test termination strain, 100 000 μs
(*d*) terminal pulse count, 3600 pulses
(*e*) conditioning stress, 10 kPa
(*f*) loading stress, 100 kPa[19–22]
(*g*) time, 15 min
(*h*) pre-load rest time, 2 min
(*j*) recovery time, 2 min.

The tests were carried out at 40°C. In order to reduce friction on the end plates, the top and bottom of the samples were dipped in silicon powder. The sizes of the samples were around:

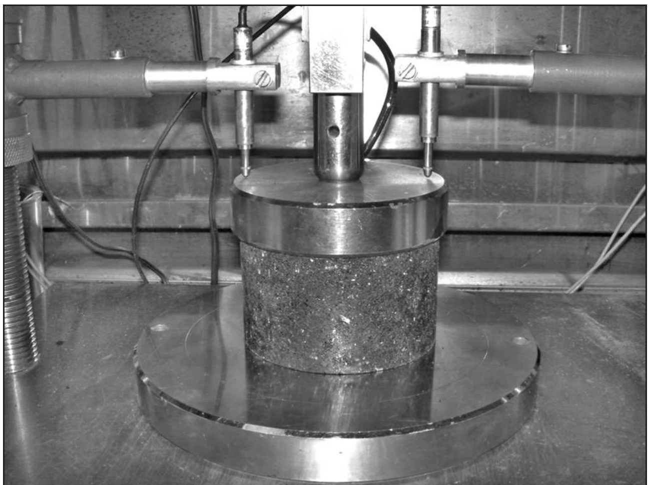

Figure 7. The configuration of the repeated load axial creep test

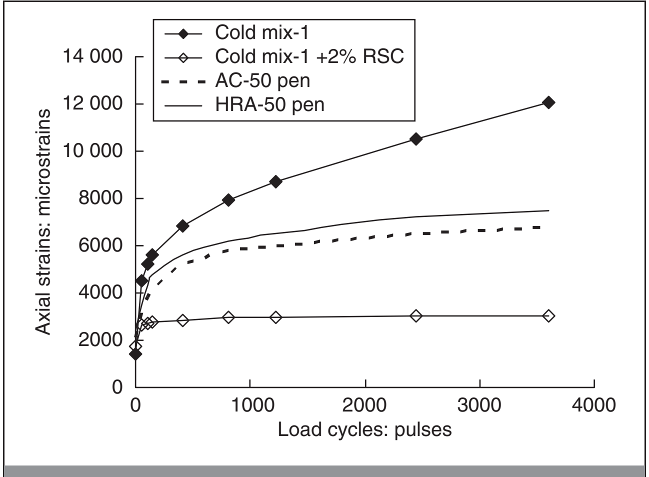

Figure 8. Cold mixes dynamic creep test results (strain plotted against load cycles) at 40°C, compared with hot mixes

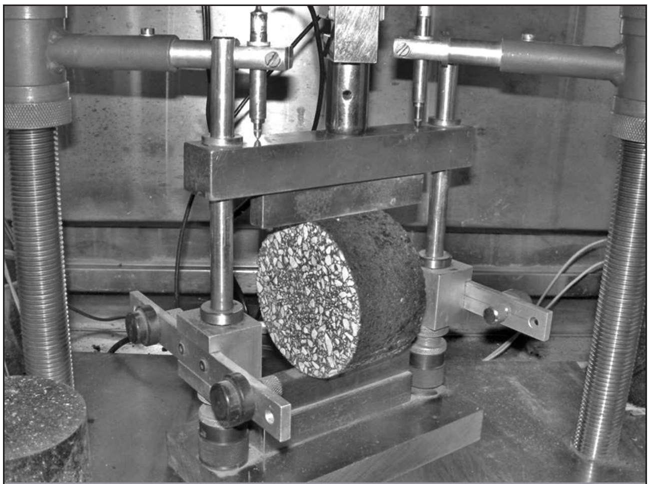

Figure 9. Fatigue test configuration

62–65 mm and 100 mm in diameter. This size of samples had been commonly used by researchers in Leeds[8,23] and is consistent with the British Standard Draft for Development DD-185: 1990.[24]

The creep performance of the cold mixes (number of load cycles plotted against cumulative strain) is shown in Figure 8. As is generally the case for creep behaviour, the creep curve can be divided into three main regions; the primary creep region where the strain rate decreases with the number of load cycles applied; the secondary creep region where the strain rate is almost constant, otherwise known as the steady-state strain rate; and the tertiary creep region where the strain rate increases rapidly up to failure.

The steady-state strain rates, or creep slope values are shown in Table 4. The results are compared with readily available data from hot mixtures.[23]

Referring to the creep test results in Figure 8, in general, the creep of the mixtures is directly related to their stiffness (ITSM) values. Naturally, a higher ITSM value leads to a higher creep stiffness value, which in turn leads to reduced permanent deformation and lower creep slope values.

It is interesting that in Figure 8, the cold mix-1 + 2% RSC mixes were found to have lower creep deformations (i.e. better performance) in comparison with the hot bituminous mixtures made with harder 50 pen. bitumen. Without cement, however, the cold mix-1 gave a lot higher deformation than the hot mixtures. Referring to Table 5, the cold mixes are clearly suitable for low to medium trafficked roads.[16]

10. FATIGUE PERFORMANCE

Fatigue is a phenomenon of fracture or failure under repeated loading. Fatigue test results can be expressed as a relationship between the number of loading cycles, N_f (pulses) to strain ($\boldsymbol{\varepsilon}$) at failure.[18] The fatigue testing configuration is shown in Figure 9. The fatigue performances of the cold mixes were compared with 14 mm maximum aggregate size asphalt concrete mixes of 100 pen. asphalt with 5% air void[25] with 5% optimum asphalt content. The fatigue lines are shown in Figure 10 (in a log–log scale).

The fatigue line equations and correlation coefficient R^2 from the fatigue tests are presented in Table 6.

Mixture	Test temp.: °C	Linear regression* equations and $R^{2\,\dagger}$	Slope of creep curve: $\mu\boldsymbol{\varepsilon}$/pulse
Cold mix-1	40	$y = 1{\cdot}42x + 6963{\cdot}1$	1·42
Cold mix-1 + 2% RSC	40	$y = 0{\cdot}02x + 2956{\cdot}1$	0·02
Asphalt concrete	40	$y = 0{\cdot}3378x + 5614{\cdot}1$	0·338
Hot rolled asphalt	40	$y = 0{\cdot}4229x + 6041{\cdot}1$	0·423

* Equations applicable to the range from 1200–3600 pulses (see Figure 9).
† R^2 values for all equations were higher than 0·95.

Table 4. Cold mix dynamic creep slope data (referring to Figure 8)

Average annual pavement temperature: °C	Heavy traffic: $>10^6$ ESA	Medium traffic: 5×10^5 to 10^6 ESA	Light traffic: $<5 \times 10^5$ ESA
>30	<0·5	0·5–3	>3–6
20–30	<1	1–6	>6–10
10–20	<2	2–10	Not applicable

ESA, equivalent standard axle

Table 5. Typical laboratory-determined minimum dynamic creep slope values[16]

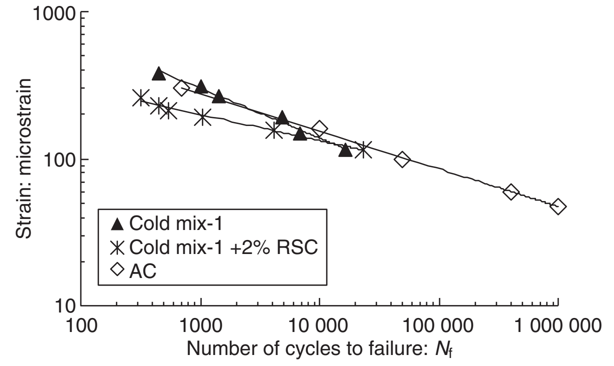

Figure 10. Cold mixes fatigue performance compared with hot mixes

Referring to Table 6 and Figure 10, it can be clearly seen that the fatigue lines of the cold mix-1 + 2% RSC were flatter than the cold mix without cement. At a projected life to failure (N_f) of 10^6 load (pulse) cycles, the cold mix-1 + 2% RSC could withstand a deformation of 59 microstrains, which was about twice the strain (deflection) of the cold mix without cement. Similarly, the number of cycles to failure (N_f) of the cold mix-1 + 2% RSC at a relatively low deflection value of 100 microstrains ($4{\cdot}84 \times 10^4$ cycles) was also much higher than that of the cold mix-1 without cement. This indicates that incorporating cement significantly improves the performance of cold mix-1, in particular at low strain levels; for example, when acting as part of a well designed pavement structure.

Figure 10 also shows that the fatigue performance of the cold mix-1 + 2% RSC compared well with the 14 mm asphalt concrete 100 pen. hot mixes.[25] However, without cement the cold mixes were inferior. This is logical, in particular when considering the air void values of the cold mixes which in general were much higher than of the hot mixes.

The stiffness of the cold mixes with cement was a lot greater than those of the hot mixes with which they were being compared. However, as fatigue is only one of many parameters that can be used to evaluate the performance of asphalt mixes, it is possible that one mixture might exhibit superior performance in one respect/area but be inferior in others. This could only be explained by the lack of repeatability of test results between different investigators.

11. CONCLUSIONS

The main conclusions drawn from this investigation are listed here.

(*a*) Cold-lay, cold-mix emulsion mixtures (cold mixes), when properly designed and at full curing, even without the addition of cement, were comparable in stiffness to hot mixtures (of equivalent grade bitumen).

(*b*) The addition of 1–2% cement by mass into cold mixes significantly improved the overall performance of the cold mix; namely the stiffness (ITSM), creep resistance and acceleration of strength gain. It did not, however, improve the fatigue performance of the cold mix beyond that of the hot mixes.

(*c*) When incorporating cement, the cold mix should be compacted soon after mixing to maximise the results and to avoid workability problems. If this is not possible the loose mixture can be kept in a sealed container and compacted after approximately 24 h (see Figure 4).

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Mixture	Equation based on strain (Figure 9)	Equation based on number of cycles to failure*	$\varepsilon(\mu\varepsilon)$ at $N_f = 10^6$ cycles	N_f (cycles) at $\varepsilon = 100\,\mu\varepsilon$
Cold mix-1 without cement	$\varepsilon = 3152{\cdot}2 \times N_f^{-0{\cdot}3397}$ $R^2 = 0{\cdot}9898$	$N_f = 2{\cdot}0 \times 10^{10}\varepsilon^{-2{\cdot}91}$ $R^2 = 0{\cdot}9898$	29	$3{\cdot}03 \times 10^4$
Cold mix-1 + 2% RSC	$\varepsilon = 679{\cdot}37 \times N_f^{-0{\cdot}1774}$ $R^2 = 0{\cdot}9899$	$N_f = 7{\cdot}0 \times 10^{15}\varepsilon^{-5{\cdot}58}$ $R^2 = 0{\cdot}9899$	59	$4{\cdot}84 \times 10^4$
14 mm asphalt concrete (100 pen. asphalt)	$\varepsilon = 1638{\cdot}4 \times N_f^{-0{\cdot}2567}$ $R^2 = 0{\cdot}9991$	$N_f = 3{\cdot}0 \times 10^{12}\varepsilon^{-3{\cdot}89}$ $R^2 = 0{\cdot}9991$	47	$4{\cdot}98 \times 10^4$

* Based on data presented in Figure 10, but with the strain plotted as the *x*-axis and the load cycles plotted as the *y*-axis.

Table 6. Fatigue line equations (exponential regression line/trend line) and coefficient of correlation (R^2)

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