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Laboratory design and investigation of the properties of continuously graded Asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt)

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Abstract

This paper discusses the laboratory design of continuously graded Asphaltic concrete (AC) mixtures containing recycled plastics aggregate replacement (Plastiphalt). Recycled waste plastics, predominantly composed of low density polyethylene (LDPE) in pellet form, were used in dense graded bituminous mixes to replace (by volume) a portion of the mineral aggregates of an equal size, i.e., 5.00–2.36 mm. The results obtained in this investigation indicate that at the same air-void content, the compacted Plastiphalt mix has lower bulk density than that of the conventional control mix. A 30% aggregate replacement by volume with the LDPE, results in a reduction in bulk compacted mix density of 16%. This reduction in density is advantageous in terms of haulage costs. LDPE partial aggregate replacement also results in a 250% times increase in the Marshall stability (strength) value and an improved Marshall quotient value (resistance to deformation). The value of creep stiffness of the Plastiphalt mix after 1 h loading at 60°C is found to be slightly lower than the control mix; however, the Plastiphalt gives 14% recovery after 1 h unloading time compared to 0.6% for the control mix. The indirect tensile stiffness modulus (ITSM) values of the Plastiphalt compacted mix were found to be lower than that of the control mix, whereas the static indirect tensile strength (ITS) values were found to be much higher. In this study, the future recyclability of the Plastiphalt was also investigated. The mechanical properties of the recycled mix were found to be equal to that of the original Plastiphalt and better than the control mixes.

Keywords: Asphaltic concrete; Mix design; Waste; Plastics; Plastiphalt

1. Introduction

The generation, handling, and safe disposal of industrial and domestic solid waste has become a major concern in the European Community. The increasing volume of wastes generated and the procedures for their disposal are now restricted by legislation. This does not limit the way in which disposal is carried out but imposes appropriate 'environmental' taxes which have prompted waste generators to implement procedures for safe disposal or if possible reuse of the wastes generated [1].

Reuse of bulk wastes is considered the best environmental alternative for solving the problem of disposal. The large volume of composite materials required for the construction and maintenance of road pavements in the UK is potentially a major area for the reuse of waste materials. Because the amount of 'new' materials like mineral aggregates required in the road construction industry is large, approximately 20,000 t per mile of motorway constructed [2,3], the environmental benefits are not only related to the safe disposal of bulk waste but also to the reduction of environmental impacts arising from the extraction of aggregates which include the loss of mature countryside, visual intrusion, heavy lorry traffic on unsuitable roads, noise, dust and blasting vibration.

In 1995, the plastic consumption in the UK was about 3,302,000 t (24,350,000 t across Western Europe). The major users of plastic are the packaging industries, consuming about 41%, 20% in building and construction, 15% in distribution and large industries, 9% in electrical and electronic, 7% in automotive, 2% in agriculture and 6% in other uses.

In the UK, the total plastic waste was estimated at around 2,158,000 t in 1995; 1,279,000 t (59.2%) arising

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from municipal solid waste, 446,000 t (20.7%) arising from distribution and large industry, 151,000 t (7%) from automotive industries, 128,000 t (5.9%) from electrical and electronics, 122,000 t (5.7%) from construction/demolition and civil works, and 32,000 t (1.5%) from agriculture.

From the total household waste in Western Europe in 1995, about 129,061,000 t; the amount of plastic waste is about 8% by weight, approximately 10,139,000 t. The largest component of the plastic waste is low density polyethylene/linear low density polyethylene (LDPE) at about 23%, followed by 17.3% of high density polyethylene, 18.5% of polypropylene, 12.3% of polystyrene (PS/extended PS), 10.7% polyvinyl chloride, 8.5% polyethylene terephthalate and 9.7% of other types [4].

1.1. Plastic recovery

Recovery is the process of obtaining materials or energy resources from solid waste. Recovered plastic might be recycled into new products or used in process engineered fuels, where collected plastic are processed with paper into fuel pellets and then used in conjunction with coal and other fuels in industrial boilers and utility plants. Only one quarter of the 16 million tonnes of all post-use plastic was recovered in Western Europe in 1995 [4]. Plastic recycling has reached 9.2%, whilst 16.8% was recovered for energy providing heat and electricity for homes and business. Recycling plastic waste from the distribution sector remains at 21.9% and from agriculture at 27.3%. Recycling of plastic packaging is also increased as the quantities of recovered domestic waste gradually increases. In 1995, material recycling of domestic waste rose from 363,000 t in 1994 to 454,000 t. In the same year, almost 2.7 million tonnes of plastic waste was turned into energy.

These facts demonstrate the immense scope still available for plastic waste recovery and encapsulation. Bituminous road surfacings offer an ideal opportunity for utilisation of large volumes of unusual plastic into a civil engineering structure with the possibility of enhancing the strength and life of these modified road-layers.

Numerous investigations have been carried out on incorporating polymer modified bitumens to improve the performance of bituminous composites. These included bitumens modified with SBS or EVA or SBR (natural and ground tyre rubber) in various concentrations. Most of the results obtained from laboratory and full-scale trials demonstrate to varying extents an improvement in the performance of these modified bituminous mixes in terms of increased resistance to permanent deformation, improvement in fatigue life, improved durability and resistance to moisture damage [5,6]. Bitumens usually form a low percentage of a bituminous road surfacing. Studies have therefore also been performed on the mineral aggregate components (coarse aggregate, sand and filler) which together form typically 94% of the bituminous composite by weight. Variations in mineral aggregate grading, mineralogy, macro and micro texture, crushing and impact strength, water absorption and trials with alternative sources (including recycled, artificial, demolition) aggregates, have all been investigated in order to improve the strength and durability of the resultant mix.

The use of polyethylene [7,8] and polypropylene [7] waste plastic as bitumen modifiers has been investigated and the results show an improvement in the quality of the binder and mix properties. The addition of 30% polyolefinic plastics (polyethylene and polypropylene) by volume of bitumen, result in an increase of Marshall stability at least of 42% [7]. However, the amount of waste plastic utilized in this modified bitumen is very small, up to 30% by weight of the bitumen, which equates to a maximum of only 1.5% by weight of total mix. This utilization though beneficial, does not provide a major contribution to the overall objective of reducing waste plastics. Furthermore, the technique of incorporating polymers into bitumen on site requires major modifications to the heating and mixing mechanisms of the bitumen tanks in order to eliminate the possibility of polymer segregation.

This paper presents a laboratory design methodology and test results of a continuously graded bituminous composite (Asphaltic concrete (AC)) containing recycled plastics aggregate replacement (Plastiphalt). The test results were compared to those obtained from a control mix having a very similar gradation manufactured with conventional mineral aggregates. The potential for recyclability of the aged Plastiphalt mixes, containing recycled waste plastic was also investigated.

2. Experimental materials and methods

2.1. Materials used and specimen manufacture

Table 1 and Fig. 1 show the aggregate gradation of the control dense graded (AC) mix selected for this investigation. The AC gradation was developed at Leeds [9] using maximum aggregate packing principles and was specifically designed to withstand combinations of heavy traffic stresses at elevated temperatures.

Table 2 shows the characteristics of the bitumens used in this investigation. Bitumen grades 50 and 100-pen were used in the control and the Plastiphalt mixes, respectively. A softer bitumen was selected for the Plastiphalt because early trials indicated that the mix was very strong and did not require the use of a hard bitumen. This has the added advantage that the mixing

Table 1
Aggregate gradations used in this investigation

Sieve size (mm)	% passing by weight	
	Control mix [9]	Plastiphalt
14	100	100
10	95.7	94.6
6.3	89.2	86.5
5.0	75.6	69.6
2.36	45.9	57.1
0.6	45.2	56.2
0.4	40.2	50.0
0.15	16.7	20.8
0.075	10	12.4

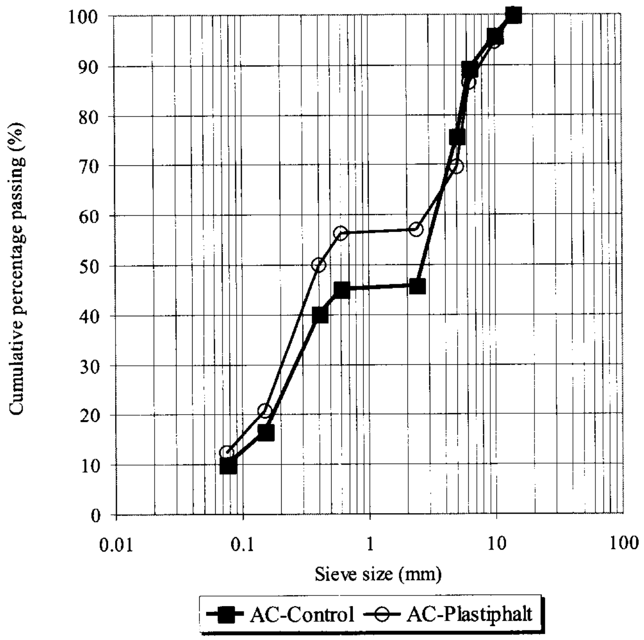

Fig. 1. Aggregate gradation lines of mixes used in this investigation.

Table 2
Characteristics of the bitumens used in the investigation

Test description	50-pen	100-pen
Penetration at 25°C (dmm)	54	98
Specific gravity	1.03	1.02
Softening point (R & B test) (°C)	48.5	45.0

and compaction temperatures of the bituminous mix, which are controlled by the viscosity of the binder, can thus be lowered.

The plastic pellets obtained were predominantly composed of LDPE of single size (5–2.36 mm). Table 3 presents some of the waste plastic characteristics. It was decided in this investigation to replace by volume the mineral aggregate fraction having the same size as the plastic pellets in the original AC mix with LDPE pellets. The aggregate gradation of the resultant Plastiphalt mix would therefore be very similar in terms of volumetric proportions to the original AC control mix. The origin of the plastic materials employed in the investigation was municipal waste (plastic bottles, plastic containers, washing-up liquid bottles, etc.).

Table 3
Characteristics of the waste plastics

Properties	LDPE
Granulate shape	Pellet
Size (mm)	5.00–2.36
Specific gravity	0.92
Softening point (°C)	120
Melting point (°C)	140

Based on the selected AC grading and the size of the waste plastic pellets, a maximum of 29.7% by weight of the total control mix was replaced with waste plastics. The main variable between the Plastiphalt and the control AC mix would therefore be the bulk density of the combined aggregate fractions. Fig. 2 shows the aggregate composition by weight of the control and the Plastiphalt mixes excluding bitumen used in this study.

The experimental mixtures were manufactured at five different bitumen contents. The Leeds design method (LDM) [10,11] was then used to obtain the optimum bitumen content (o.b.c.) of the design mixture. At o.b.c, further investigations and tests were carried out to fully characterise the properties of the design mixture.

The mixing and compaction temperatures need to be carefully controlled to cater for the differing softening points of the two plastic types. At worse, with minimal temperature control, the plastics behave as inert aggregates contributing to the continuation of the mineral

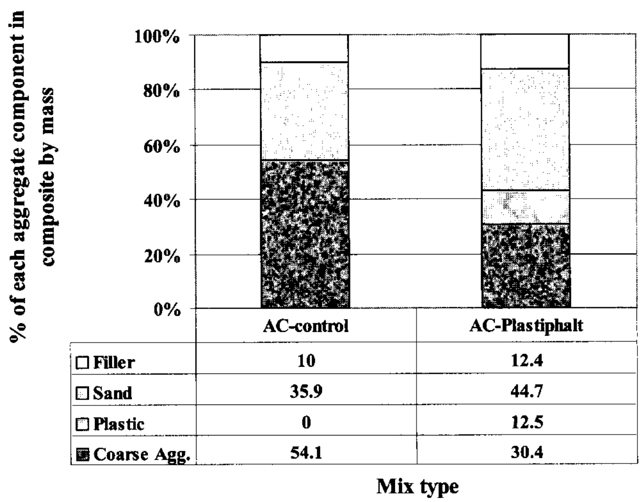

Fig. 2. Illustration of the various aggregate components by mass for the conventional and Plastiphalt mixes.

aggregate interlock. On the other hand, if the mixing and compaction temperatures are carefully selected, the plastics can be compacted near their softening point temperatures thus creating a much greater improvement in the resultant mix strength as the semi-molten plastic granules key into and strongly adhere to the surrounding mineral aggregate particles.

For the control AC mix, the combined aggregates and bitumen were mixed in a thermostatically controlled preheated twin paddle mixer at a mixing temperature of 150°C which resembles the optimum bitumen viscosity of 0.2 Pa s. On the other hand, a compromise between the optimum bitumen viscosity and the softening and melting points of the waste plastics had to be considered for the Plastiphalt mixes. This is because once the mixing temperature exceeds the melting point, the plastics transform into a low viscosity fluid, which flows and reduces the workability of the mix. It is recognised that for optimal compaction the viscosity of the bitumen should lie between 2 and 20 Pa s [12]. Compaction of all specimens was carried out using a gyratory compactor (Gyropac) at 125°C. The energy of compaction applied with the Gyropac was set at 240 kPa vertical pressure and 120 gyratory compactive revolutions at a fixed angle of gyration of 2°. This is classified as heavy compaction suitable for high levels of traffic and is equivalent to 75 blows each end of the specimen with a Marshall hammer.

2.2. *Marshall stability and flow tests*

Marshall stability and flow tests were carried out on compacted specimens at various bitumen contents according to BS 598: part 107 [13]. The Marshall test is an empirical test in which cylindrical compacted specimens, 100 mm diameter by approximately 63.5 mm high are immersed in water at 60°C for 30–40 min and then loaded to failure using curved steel loading plates along a diameter at a constant rate of compression of 51 mm/min. The Marshall stability value (in kN) is the maximum force recorded during compression whilst the flow (in mm) is the deformation recorded at maximum force.

The ratio of stability (kN) to flow (mm) is termed the Marshall quotient (MQ) (kN/mm) and is an indication of the stiffness of the mix. The MQ has been reintroduced in Draft BSEN 12697-34: Bituminous mixtures test methods for hot mix Asphalt – Part 34: Marshall test. The aforementioned BS is set to supersede BS 598 – Part 107.

2.3. *Indirect tensile stiffness modulus test*

Stiffness modulus is considered to be a very important performance characteristic of the roadbase and basecourse layers. It is a measure of the load-spreading ability of the bituminous layers and controls the level of traffic induced tensile strains at the underside of the roadbase which are responsible for fatigue cracking together with the compressive strains induced in the subgrade that can lead to permanent deformation. The ITSM test defined by BS DD 213 (1993) [14] is a non-destructive test and has been identified as a potential means of measuring this property. Fig. 3 shows typical ITSM test equipment.

Under uniaxial loading the stiffness modulus is generally defined as the ratio between the maximum stress and the maximum strain. In visco-elastic materials such as bituminous composites, this is often referred to as the complex modulus. Because of the viscous component in bituminous materials, the strain always lags behind the stress, and this lag is known as the phase angle. The ITSM S_m in MPa is defined as

$$S_m = \frac{L(v + 0.27)}{(Dt)},$$

where L is the peak value of the applied vertical load (N), D the mean amplitude of the horizontal deformation obtained from two or more applications of the load pulse (mm), t the mean thickness of the test specimen (mm), and v is the Poisson's ratio (a value of 0.35 is normally used).

During testing, the rise time, which is measured from when the load pulse commences and is the time taken for the applied load to increase from zero to a maximum value is set at 124 ± 4 ms. The load pulse, defined as the period from the start of the load application until the start of the next load application is equated to 3.0 ± 0.05 s. The peak load value is adjusted to achieve a peak transient horizontal deformation of 0.005% of the specimen diameter. The test is normally performed at 20°C, but for this investigation, additional tests were performed at 40°C and 60°C.

2.4. *Indirect tensile strength test (ITS)*

In the indirect tensile strength test (ITS), cylindrical specimens are subjected to compressive loads, which act parallel to and along the vertical diametral plane using the Marshall loading equipment. This creates uniform tensile stresses perpendicular to the direction of applied load and along the vertical diametral plane, which ultimately causes the specimen to fail splitting along the vertical diameter. Based upon the maximum load carried by a specimen at failure, the ITS is calculated from the following equation:

$$\text{Indirect tensile strength (ITS)} = \frac{2P_{max}}{\pi t d},$$

where P_{max} is the maximum applied load, t the average height of specimen, and d is the diameter of specimen.

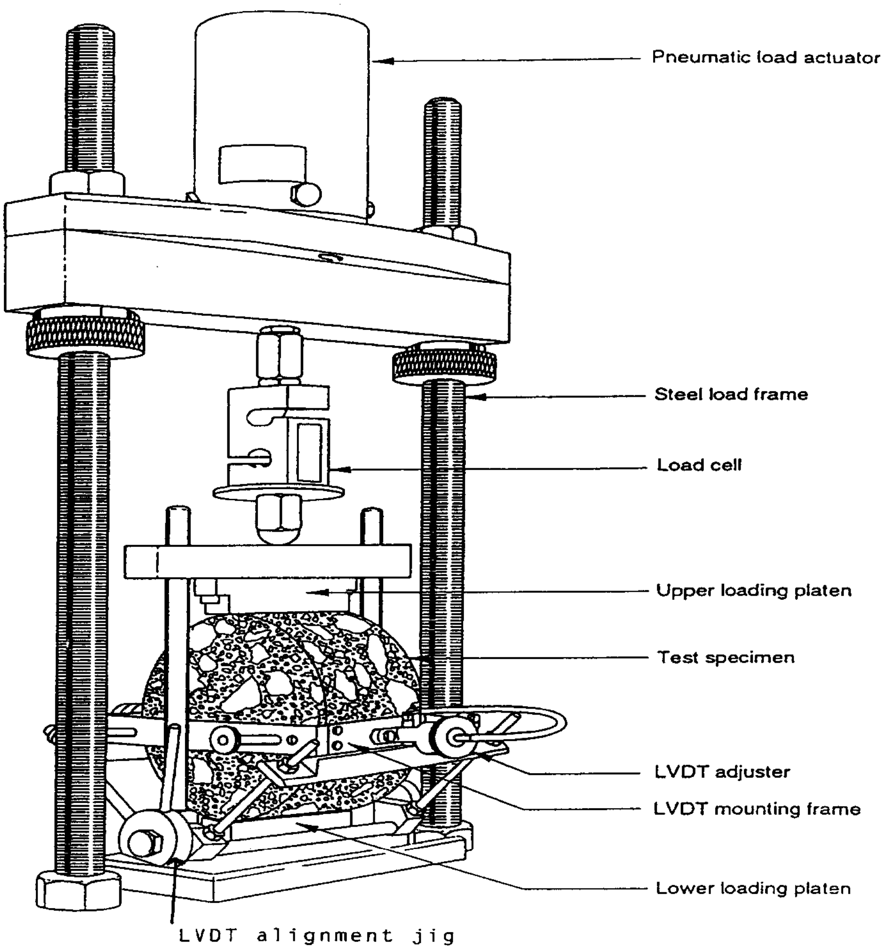

Fig. 3. Typical ITSM test equipment [15].

2.5. Creep stiffness

The creep test is carried out either in the static or dynamic mode of loading. Each test typically lasts two hours, and gives results which allow the characterisation of the mixes in terms of their long-term deformation behaviour [15]. Better correlation in terms of mix ranking, with respect to creep deformations or strain rates, has been shown to exist between the repeated load axial (RLA) and the wheel tracking tests than the ranking produced by the static creep test [16].

Typical conditions under which the unconfined static uniaxial creep test is carried out are: (a) standard test temperature 40°C, for very hot climates 60°C; (b) pre-loading for 2 min at 0.01 MPa, as a conditioning stress; (c) constant loading stress during the test equal to 0.1 MPa; (d) duration of test: 1 h loading and 1 h unloading. During the test, axial deformation is measured as a function of time. Thus knowing the initial height of the specimen, the axial strain, ε, and therefore the stiffness modulus S_{mix}, at any loading time can be determined:

$$S_{mix} = \text{applied stress } (\sigma) \div \text{cumulative irrecoverable axial strain } (\varepsilon).$$

For the unconfined repeated load uniaxial creep test [17], which was carried out in this investigation, the applied stresses are as before, but the pulse loading durations vary slightly; pulse width = 1 s, pulse period = 2 s, test terminated after 3600 pulses giving an accumulated loading time of 1 h.

2.6. Adhesion testing

Detachment of bitumen from the aggregate (or stripping) is associated with mixes which are susceptible to long-term moisture damage. There is little risk of stripping in low void content dense Asphalts or Macadams. In materials that are permeable to water, even those that are relatively dense, there is a risk of stripping, resulting in a loss of internal cohesion and possibly disintegration of the surfacing. The potential for stripping is a function of the affinity between the aggregate and the bitumen and its consequent ability to resist the displacing effect of water.

Immersion mechanical tests – these involve measurement of a change in a mechanical property of a compacted bituminous mix after immersion in water. Thus, the ratio of the property after immersion divided by the initial property is an indirect measure of stripping. Probably the most popular is the Marshall test; the ratio of Marshall stability of bituminous specimens after wet conditioning to identical specimens not subjected to the conditioning process is known as the retained Marshall stability and is usually quoted as a percentage. The test method selected for this investigation is based on the AASHTO T165-77, the test consists of conditioning specimens at 60°C for 24 h in water and then testing them for Marshall stability.

3. Experimental results

3.1. Determination of the optimum binder content (o.b.c.)

The o.b.c for both mixtures was determined using the LDM [10,11]. The LDM recommends that the o.b.c for dense graded mixtures should be obtained as the arithmetic mean of the o.b.c at maximum compacted mix density, minimum voids in the mineral aggregate (VMA), and maximum stability. The VMA is defined as the intergranular void space between the aggregate particles in a compacted specimen and is expressed as a percentage of the bulk volume of the compacted specimen [18]. The MQ (kN/mm) values are defined as the ratio of Marshall stability (kN) to flow (mm). At o.b.c the compacted mix must possess adequate porosity, VFB, VMA, flow, creep stiffness and minimum air permeability. Compacted mix densities are calculated according to BS 598: Part 107 [13]. Table 4 presents the results of testing compacted specimens at a range of bitumen contents.

The o.b.c for the control mix was calculated at 5.0% which agrees with previous investigations [9], whilst the o.b.c for the Plastiphalt mix was determined at 6.0%. Tables 5 and 6 show the Asphalt Institute Mix Design Criteria for satisfactory paving mixes and the results obtained in this investigation exceed all design requirements.

3.2. Mechanical properties of mixes at o.b.c.

Further characterisation tests were carried out at the o.b.c value for each mix type and the results of all tests conducted on the design mixes are shown for comparison purposes in Table 7. All the results are obtained from compacted specimens at the o.b.c of each mix type and each result is from an average of three test specimens.

Table 4
Design parameters values of the control and Plastiphalt mixes

Control mix [9]					Plastiphalt mix				
Bitumen content (%)	Mix density (g/cm^3)	VMA (%)	Stability (kN)	MQ (kN/mm)	Bitumen content (%)	Mix density (g/cm^3)	VMA (%)	Stability (kN)	MQ (kN/mm)
4.5	2.34	16.2	15.6	4.45	5.0	1.92	15.42	25.50	3.75
5.0	2.37	15.4	16.9	4.69	5.5	1.96	14.38	29.61	4.23
5.5	2.36	16.2	16.5	4.55	6.0	1.99	13.63	41.32	5.23
6.0	2.35	16.9	15.9	3.58	6.5	1.98	14.35	24.53	3.14
					7.0	1.96	15.56	21.28	2.49

Table 5
Asphalt institute Marshall mix design criteria

Marshall method	Light traffic		Medium traffic		Heavy traffic	
Mix criteria	Min	Max	Min	Max	Min	Max
Compaction, number of blows each end of specimen	2 × 35		2 × 50		2 × 75	
Stability (N)	3336		5338		8006	
Flow (0.25 mm)	8	18	8	16	8	14
% air-void	3	5	3	5	3	5
% VMA	See Table 6					
% voids filled with bitumen (VFB)	70	80	65	78	65	75

Table 6
Minimum percent VMA

Nominal maximum Particle size (mm)	Minimum VMA (%)		
	Design air-voids		
	3.0%	4.0%	5.0%
9.5	14.0	15.0	16.0
12.5	13.0	14.0	15.0
19.0	12.0	13.0	14.0

3.2.1. *Mix density characteristics*

As expected, the compacted density of the Plastiphalt mixes were lower than that of the control mix. A 29.7% coarse aggregate replacement by volume with the lower specific gravity LDPE, results in a 16% reduction in bulk density of the compacted mix. The reduction in bulk compacted density is accompanied by a reduction in the VMA, which indicates a tighter, more dense aggregate skeleton. This result would give an advantage in terms of haulage costs.

3.2.2. *Marshall stability, flow, Marshall quotient and retained stability*

The results show that the Plastiphalt mixes have superior Marshall stability values compared to the control mix. A stability increase of nearly 2.5 times indicates that the Plastiphalt mixes are much stronger than the control mix. This strength can be achieved because the Plastiphalt is mixed and compacted at the correct preselected temperatures. The flow value of the Plastiphalt mix is also higher than the control mix due to the more flexible plastic component of the mix. Although the stability value of the Plastiphalt mix at OBC may at first instance seem unrealistically high, it must be noted that recent advancements in bituminous mix design have created very high performance mixtures. For example, recent work at CEMU has resulted in AC made with 10/20 pen. Binders to exhibit Marshall stability values in excess of 40 kN [9].

Table 7
Mix properties of control and Plastiphalt mixes

Properties	Mix type	
	Control mix [9]	Plastiphalt mix
1. OBC (%)	5.0	6.0
2. Mix density (gm/cm^3)	2.37	1.99
3. Porosity (%)	3.7	2.9
4. VMA (%)	15.5	13.6
5. Marshall stability at failure (kN)	16.9	41.3
6. Flow (mm)	3.65	7.90
7. MQ (kN/mm)	4.63	5.23
8. % retained Marshall stability (%)	85	100
9. Creep stiffness at 1 h loading at: (MPa)		
(a) 40°C	13.0	7.23
(b) 60°C	7.99	6.55
10. Percentage recovery after 1 h unloading at 40°C (%)		
(a) 40°C	2.75	14.21
(b) 60°C	0.60	12.11
11. Indirect tensile stiffness modulus at (MPa)		
(a) 20°C	5683	2815
(b) 40°C	865	770
(c) 60°C	283	235
12. Static indirect tensile strength at 20°C (kPa)	1047	1508

Conventional dense graded mixes normally combine high stability with low flow values and hence high MQ values indicating a high stiffness mix with a greater ability to spread the applied load and resist creep deformation. Care must be exercised with very high stiffness mixes due to their lower tensile strain capacity to failure i.e. such mixes are more likely to fail by cracking particularly when laid over foundations which fail to provide adequate support. Although the Marshall stability of the Plastiphalt mix is much higher than the control mix, the flow values of Plastiphalt mixes are also greater indicating higher strain capacities to achieve failure. The value of MQ of the Plastiphalt is higher than that of the control mix. It is well recognised that The MQ (a form of pseudo stiffness) is a measure of the material's resistance to shear stresses, permanent deformation and hence rutting [12].

3.2.3. *Creep stiffness*

The creep stiffness is indicative of the resistance to permanent axial deformation and for bituminous specimens is basically obtained from the ratio of applied stress to cumulative compressive strain at a defined temperature and time of loading [19]. Based on the results shown in Table 7, the creep stiffness of the Plastiphalt mixes were found to be lower (nearly half) the stiffness values of the control mix at 40°C and an improved (82% of control mix) at 60°C.

Under repeated loading, larger strains may occur due to the effect of the pulsed loading on the aggregate skeleton [16]. It has been suggested that the static creep test does not reflect the performance of modifiers, which improve the values of elastic recovery of a material, as well as repeated loading conditions [20]. The creep recovery values of the Plastiphalt after 1 h unloading were found to be 14% and 12% at 40°C and 60°C test temperatures, respectively; whilst 3% and 0.6% recovery values were recorded for the control mix at 40°C and 60°C test temperatures, respectively.

3.2.4. Tensile properties

Fig. 4 shows the ITSM results for both the Plastiphalt and control mixes at 20°C, 40°C and 60°C. The results indicate that the ITSM values of the control mix are higher than that of the Plastiphalt mix, especially at 20°C, but that at higher temperatures the values tend to converge.

However, the ITS of the Plastiphalt specimens were higher than the control mix. This indicates that the AC containing recycled plastics aggregate replacement (Plastiphalt), although not as stiff as the control mix in dynamic loading (ITSM), (which would imply greater values of dynamic strains recorded in the test), nonetheless have much higher values of tensile strength at failure ITS under static loading. This would further imply that the Plastiphalt mix appears to be capable of withstanding much larger tensile strains prior to cracking.

3.2.5. Resistance to stripping

By subjecting specimens to immersion in water for 24 h at 60°C, the design mix was shown to perform better than the control mix in terms of its resistance to moisture damage. The results indicate that the Plastiphalt mix retained 100% of its pre-conditioned stability values. In comparison, the retained stability of the control mix after immersion is only 85%.

3.2.6. Fatigue behaviour

At the time of writing this paper, fatigue tests on the Plastiphalt had not been completed. Nonetheless, limited indirect tensile fatigue data indicate that in terms of initial tensile strain vs number of cycles to fatigue failure, Plastiphalt samples show on average a 50% improvement in fatigue life. Detailed investigations are currently being carried out at CEMU.

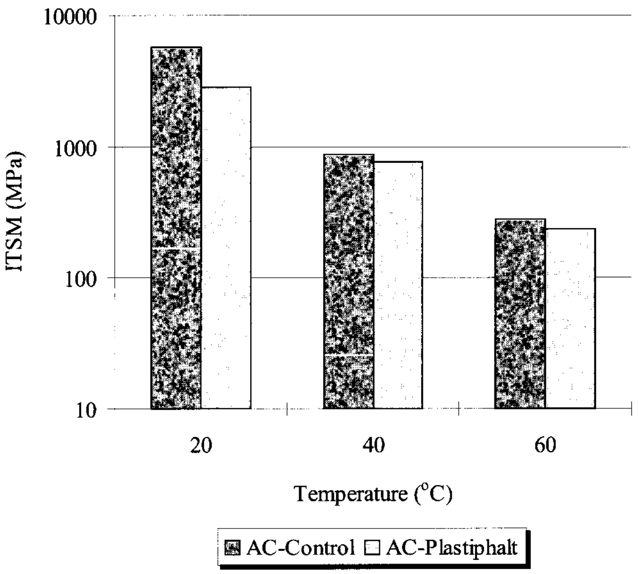

Fig. 4. The ITSM values of mixes.

3.3. Properties of the recycled mixes

One of the main concerns that confronts material engineers when considering utilising waste materials in the manufacture of bituminous mixtures is the question of future recyclability [21]. To investigate the potential for recycling the Plastiphalt mix at the end of its design life, compacted specimens were initially loosened (pulverised) into small particles in an effort to simulate the planing process which is carried out onsite on bituminous pavement layers at the end of their service lives. The loose material which is composed of bitumen coated aggregates of various sizes were placed in an oven at 85°C for 120 h. This process simulates long-term ageing equivalent to approximately 15 years in situ. The same procedure is followed in the SHRP long-term oven ageing test which is carried out on compacted specimens, except that in this investigation the specimens were pulverised to create the worst possible conditions of ageing and oxidation. At the end of the ageing process, the aged mixture was reheated to mixing temperature and a small quantity of bitumen (1.0%) was introduced whilst mixing. The recycled mixture was then compacted at the same compaction temperature as in the main investigation. The recycled specimens were subsequently tested for; Marshall stability at a predetermined flow (deformation) value, ITSM, ITS and dynamic creep tests.

Table 8, Figs. 5 and 6 present the test results of the recycled Plastiphalt mix compared with the original Plastiphalt. By comparing the test results of the control mix from Table 7 with the results of the original and

Table 8
Mix properties of original and recycled Plastiphalt mixes

Properties	Plastiphalt mixes	
	Original	Recycled
1. Mix density (gm/cm^3)	1.99	2.01
2. Marshall stability at 4 mm flow (kN)	26.9	34.8
3. MQ (kN/mm)	6.7	8.7
4. Creep stiffness at 1 h loading (dynamic) at 60°C (MPa)	6.55	11.36
5. Percentage recovery after 1 h unloading at 60°C (%)	12	18
6. Indirect tensile stiffness modulus at (MPa)		
(a) 20°C	2815	6047
(b) 40°C	770	2512
(c) 60°C	235	727
7. Static indirect tensile strength at (kPa)		
(a) 20°C	1508	2065
(b) 40°C	706	1133
(c) 60°C	318	493

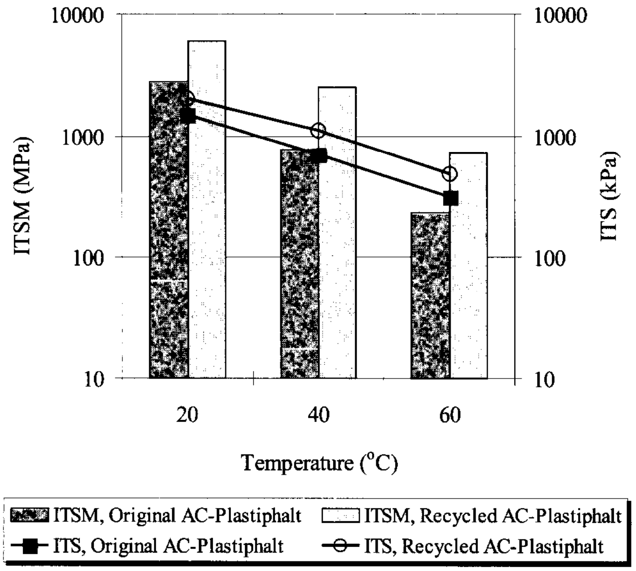

Fig. 5. ITSM and ITS values of the original and recycled Plastiphalt mixes.

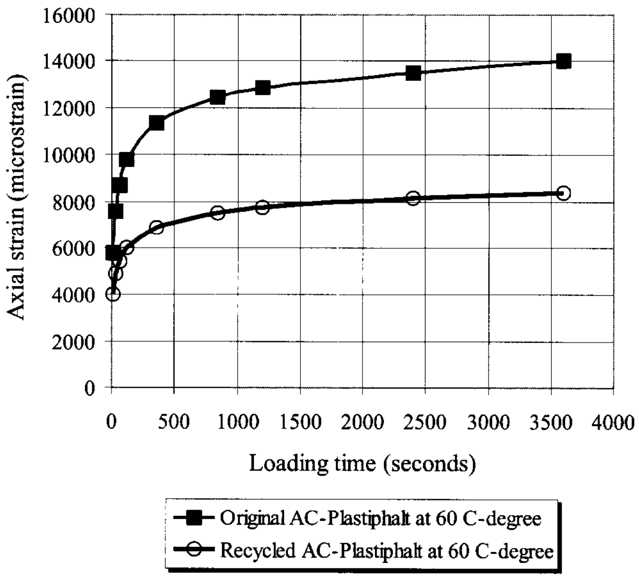

Fig. 6. Measured strain values from the dynamic creep test of the original and recycled Plastiphalt mixes.

aged Plastiphalt, it can be seen that the aged Plastiphalt has outperformed all other mixes in all the tests conducted including the ITSM and ITS tests. This is due to the fact that the mix ageing process has caused the original bitumen layer coating the aggregates to oxidise and harden, the binder hardening causes an increase in the stiffness of the mix.

The creep stiffness and the axial strain results at 60°C from the dynamic creep test showed improved performance. Furthermore, the creep recovery properties of the recycled mix were not reduced as a result of the binder ageing process. At 60°C the percentage recovery after 1 h unloading time during creep testing are 18% and 12% for the recycled and original Plastiphalt mixes, respectively. Increasing the mix stiffness as a result of binder ageing without losing the resilient/rebound properties was totally unpredictable and was a remarkable feature of Plastiphalt mixes. This result implies that for future work, the use of harder bitumens (50-pen) in the manufacture of Plastiphalt is highly recommended.

The test results indicate that the AC composite containing recycled plastics aggregate replacements are easily recyclable into bituminous composites at the end of their design lives and should not cause environmental concerns with respect to disposal.

4. Potential applications

Increased confidence in the performance of bituminous composites containing solid wastes would be of obvious benefit not only to the construction industry but also to the producers of these wastes who are under increasing pressure to locate more environmentally friendly means of encapsulating these wastes.

The stiffer variations of Plastiphalt can be employed either for new construction or for refurbishment, e.g., industrial floors, warehouses, distribution centres, workshops, harbours, road crossings, bus terminals, parking areas with heavy traffic, aprons and airport pavements, deicer platforms, holding bays, taxiways, hangar pavements and cargo centres. Hence, some of the potential beneficiaries include, city councils, airport authorities, port authorities, heavy duty carpark owners and large industrial warehouse owners.

5. Conclusions

1. The incorporation of LDPE recycled plastics and manufacture of Plastiphalt mixes requires no modification to existing Asphalt production plant facilities and techniques.
2. The Plastiphalt mixes result in lower densities than conventional/control mixes containing mineral aggregate only. A 29.7% aggregate replacement by volume with the LDPE, results in a 16% reduction in unit weight of the mix. This result could be advantageous in terms of haulage costs or when surfacing multistorey car parks and bridge decks.
3. The Plastiphalt mixes have much higher stabilities, approximately 2.5 times that of the control mixes. The recorded flow values were also higher indicating that the mixes were both stronger and more elastic.
4. In terms of creep stiffness, the Plastiphalt mixes were found to have lower values than the control mix. However, the Plastiphalt mixes provide a remarkable

14% elastic recovery after 1 h unloading time at 40°C test temperature.

5. The ITSM values of the Plastiphalt are found to be lower than that of the control mix, but ITS value was found to be higher in the Plastiphalt mixes.
6. The Marshall flow and ITS results indicate that unlike conventional mixes which tend to reduce in strain capacity to failure as the strength of the mix increases, Plastiphalt mixes combine increased strength with improved deformation capacity.
7. Overall, the mechanical properties of aged recycled Plastiphalt mixes containing plastic aggregate replacement are superior to those of the control mixes entirely composed of mineral aggregates.

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