FLY ASH BOUND MIXTURES
RECYCLED, COST, ENERGY AND CARBON CONSIDERATIONS

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ABSTRACT

Fly ash bound mixtures (FABM) have now been used for 12 years in UK pavements. Their performance has been and continues to be excellent. This paper discusses the recycled content, cost, energy consumption and embodied carbon content of FABM. This is examined by considering the constituents of FABM and the method of production. The paper then compares the results for FABM with asphalt and then, more relevantly, on a comparative pavement basis. Conclusions are drawn and pointers suggested to where further improvements can be made.

1. Introduction

In this age of global warming and limited resources, there is increasing pressure on private individuals and business to reduce their impact on the environment. The use of recycled materials and industrial by-products, particularly for construction, is viewed in some quarters as an integral part of this drive to greater sustainability. In road construction, one of the ways to help attain this goal is the greater employment of hydraulically bound mixtures (HBM).

HBM are materials that use hydraulic binders to produce pavement bases and sub-bases. Hydraulic binders are eminently appropriate to produce sustainable pavement layers;

- firstly for their capability to utilise by-products in themselves;
- secondly for their ability to treat uniquely a significantly wide range of materials including other by-products, recycled materials, soils and poor quality aggregates;
- and thirdly, for the fact the treatment process requires no heat.

One example of HBM is Fly Ash Bound Mixtures (FABM). FABM use fly ash from coal fired power stations in conjunction with lime (either quick or hydrated), or a source of lime, as the hydraulic combination or binder. This results in sustainable mixtures, reliant on the minimal use of manufactured resources. This paper focuses on this illustrating how FABM can contribute to the drive for greater sustainability in road construction.

2. Fly Ash Bound Mixtures (FABM) for highways and other pavement

Fly ash bound mixtures (FABM) and soil treated with fly ash (SFA) are mixtures of fly ash and other constituents that have a water content compatible with compaction by rolling and a performance that relies on the pozzolanic properties of the fly ash.

The term fly ash refers to coal fly ash, also known as PFA (Pulverized Fuel Ash) in the UK. Fly ashes from UK power stations are predominantly siliceous materials and pozzolanic, which means in the presence of lime [CaO or $Ca(OH)_2$], they set and harden when in contact with water. For FABM, the ash is usually conditioned, i.e. moistened, material or, less frequently, dry run-of-station ash. Conditioned fly ash can be fresh or stockpiled material.

3. Characteristics, performance and durability

In FABM and SFA, fly ash is the main binder constituent, with quick or hydrated lime the other constituent. Cement can substitute for lime but is not as effective in mobilising the full pozzolanic and thus cementing potential of the fly ash (Table 1).

Table 1: Typical Compressive strength of a treated fly ash @ 20C (MPa)

Age of test of 1:1 sealed cylindrical specimens	Fly ash with 2.5% CaO	Fly ash with 5% CaO	Fly ash with	Fly ash with
			7% CEM 1	9% CEM 1
7 days	1.5	2.0	3.0	5.0
28 days	4.0	4.0	4.0	8.0
91 days	5.0	7.5	6.0	9.0

Compared to mixtures based on cement, FABM and SFA based on lime are slow-setting, slow-hardening, self-healing mixtures. This more protracted rate of hardening has distinct advantages in pavement construction.

- In the short term, they have the versatility of unbound materials with extended handling times and the ability to sustain trafficking before or whilst setting.
- In the medium term, because of their pozzolanicity, they possess a hydraulic reserve and thus autogenous properties, which allows them to re-heal should say cracking occur under differential settlement or traffic.
- In the long term, they develop significant stiffness and strength with the performance and durability of bituminous and cement bound mixtures.

Twelve years after their first use in the UK, actual performance has proved and continues to be excellent (ref 1).

4. Mixture design and FABM examples

In order to examine recycled content, cost, energy and embodied carbon (eCO_2), it is necessary to describe the various FABM types and typical constituent proportions. Examples of FABM in accordance with BS EN 14227-3 (ref 2) are given in Table 2.

Table 2: FABM types with constituent proportions as a percentage by dry mass

FABM type	Aggregate nature	Conditioned fly ash	CaO or Ca(OH)2	CEM I	Typical water content (%)
1, 2	Well-graded	8.5 – 13	1.5 – 3	-	6 – 8
1, 2	,,	5 – 7 (dry*)	1 - 1.5*	-	5 – 7
1, 2	,,	6 – 8	-	2 – 4	6 – 8
3	Sand	9 – 12	2 – 4	-	~ 10
3	,,	6 – 8	-	2 – 4	~ 10
4	Declared	12 – 21	3 – 4	-	Depends on agg.
4	,,	10 – 20	-	4 – 5	Depends on agg.
5	Fly ash	93 – 97	3 – 7	-	~20
5	,,	90 – 95	-	5-10	~20
SFA	Soil	6 – 8 (dry*)	1 – 2*	-	Depends on soil
SFA	,,	3 – 6	-	2 – 4	Depends on soil

*Examples are illustrative proportions for factory-blended lime with dry fly ash

5. Pavement design comparisons

FABM pavements have been used in the UK for base and sub-base applications for 12 years. One particular type of FABM known as GFA (granular material treated with fly ash) and used here as the example to illustrate the benefits of FABM, has become the mixture of choice in Staffordshire for base and sub-base.

Under current BS EN terminology, GFA is actually designated FABM 1 or 2, a well-graded 0/31.5mm mixture of aggregate (85%), conditioned fly ash (12%) and lime (typically 3%). It has been available in Staffordshire on a ready-mixed basis for a number of years, using site arisings, including planings, as the aggregate.

The pavement designs employed by Staffordshire Highways evolved in 1996 from designs prepared by one of the authors of this paper. They were based on continental experience of FABM and other hydraulically bound mixtures (Ref 3) and were used in Staffordshire for the first time in 1997 for the full-depth reconstruction of the A52 at Kingsley Bank, Froghall, see Fig. 1. A 10-year study of the performance of this 1 km reconstruction was reported at the 2008 LJMU conference (Ref 1).

These designs have been available at www.ukqaa.org since 1999 and as a result have now been proven over more than 10 years in more than 50 schemes. They have produced robust and durable pavements. The Highways Agency (HA) also allows FABM 1 for base application across the full traffic spectrum. These designs are found in HD26 (Ref 4). However, to the authors' knowledge, FABM have not been used in an HA pavement and thus the designs in HD26 do not have the same pedigree of use as the UKQAA designs. However, it is acknowledged here that the HD26 designs are the more likely to be used should other authorities decide to follow Staffordshire’s example.

Figure 1 – Laying FABM 1 in Staffordshire

To this end, and in order to permit recycled content, cost, carbon and energy comparisons later in this paper, a design comparison between FABM 1 and asphalt pavements has been prepared in Table 3 in accordance with HD26 and for the traffic categories defined by HAUC (Ref 5). For normality and ease of comparison, alternatives are shown for pavements founded on what is defined in HD26 as foundation category 2. This is a sub-base of Type 1 granular material or equivalent.

The comparison asphalt pavement uses a base of DBM50 and the FABM pavement, a base of FABM 1 to strength class T3 (i.e. HBM category B), both in accordance with Figure 2.1 in HD26. Experience has shown that FABM 1 to T3 strength category (compressive strength class ~ C5/6) is readily achievable with graded recycled aggregate of reasonable cleanliness and strength.

It should also be noted that Table 3 highlights the increased depth of asphalt binder course required by HD26 for FABM 1 pavements for the traffic levels required by HAUC Road Types 1 & 2. Experience elsewhere indicates that this is not necessary but nevertheless is adhered to here for the comparisons.

Table 3: HD26 design comparison of FABM 1 (T3) and asphalt (HDM50) pavements on foundation category 2 (Type 1 granular material)

HAUC road type	4	4	3	3	2	2	1	1
Traffic	0.5 msa	0.5 msa	2.5 msa	2.5 msa	10 msa	10 msa	30 msa	30 msa
Pavement Type to Fig 2.1 in HD26	DBM50	FABM1 (T3)	DBM50	FABM1 (T3)	DBM50	FABM1 (T3)	DBM50	FABM1 (T3)
Surface course	40mm TSCS	40mm TSCS	40mm TSCS	40mm TSCS	40mm TSCS	40mm TSCS	40mm TSCS	40mm TSCS
Binder course	60mm DBM50	60mm DBM50	60mm HDM50	60mm DBM50	60mm DBM50	100mm DBM50	60mm DBM50	120mm DBM50
Base	100mm DBM50	150mm FABM1	120mm DBM50	150mm FABM1	170mm DBM50	170mm FABM1	210mm DBM50	190mm FABM1
TOTAL	200mm	250mm	220mm	250mm	270mm	310mm	310mm	350mm

It can be seen that FABM pavements are between 30 and 50mm or an average of 40mm thicker than asphalt pavements.

6. Recycled content of FABM pavements

Because of their nature and their need just for cold mixing, it is well known that hydraulic binders or hydraulic combinations are more suitable than bitumen alone for the treatment of recycled/reclaimed aggregates and or lower quality materials. Thus for FABM 1, it is possible to use 100% recycled aggregate based on arisings or planings as has been the case in the UK for at least a decade now. Bearing in mind the fact also that fly ash constitutes the bulk of the binding element in FABM 1; it is only lime, at no more than 3% content, that is non-recycled material. Therefore for comparison purposes, FABM 1 consists effectively of 100% recycled content.

For DBM50 binder and base course on the other hand, the current maximum possible recycled content is 50%. If these proportions and those for FABM earlier are used in the pavement comparisons illustrated in table 3, it is possible to show in Table 4 using depth in mm, the quantity of construction based on virgin natural materials for each of the pavements. Table 4 shows that compared to the asphalt pavements, FABM pavements have just 50 to 60% the virgin natural aggregate requirement of asphalt pavements.

Table 4: Depth in mm of non-recycled material in Table 3 pavements

HAUC road type	4	4	3	3	2	2	1	1
Traffic	0.5 msa	0.5 msa	2.5 msa	2.5 msa	10 msa	10 msa	30 msa	30 msa
Pavement Type to Fig 2.1 in HD26	DBM50	FABM1 (T3)	DBM50	FABM1 (T3)	DBM50	FABM1 (T3)	DBM50	FABM1 (T3)
Surface course	40mm	40mm	40mm	40mm	40mm	40mm	40mm	40mm
Binder course	30mm	30mm	30mm	30mm	30mm	50mm	30mm	60mm
Base	50mm	0mm	60mm	0mm	85mm	0mm	105mm	0mm
TOTAL	120mm	70mm	130mm	70mm	155mm	90mm	175mm	100mm

7. Cost of FABM pavements

A similar exercise can be used for cost comparison. Experience in Staffordshire and elsewhere indicates that the laid price for FABM 1 is circa £50/m^3. Using this figure for FABM 1, and £100/m^3 for DBM binder course and base, and £125/m^3 for surface course, Table 5 can be produced to illustrate the laid cost of a FABM pavement compared to the asphalt pavement.

Table 5: Cost comparison in £/m^2 of FABM1 and HDM50 pavements in Table 3

HAUC Road Type	4	4	3	3	2	2	1	1
Traffic	0.5 msa	0.5 msa	2.5 msa	2.5 msa	10 msa	10 msa	30 msa	30 msa
Pavement Type to Fig 2.1 in HD26	DBM50	FABM1 (T3)	DBM50	FABM1 (T3)	DBM50	FABM1 (T3)	DBM50	FABM1 (T3)
Surface course	£5.00	£5.00	£5.00	£5.00	£5.00	£5.00	£5.00	£5.00
Binder course	£6.00	£6.00	£6.00	£6.00	£6.00	£10.00	£6.00	£12.00
Base	£10.00	£7.50	£12.00	£7.50	£17.00	£8.50	£21.00	£9.50
TOTAL	£21.00	£18.50	£23.00	£18.50	£28.00	£23.50	£32.00	£26.50

Compared to the asphalt pavements considered here and the prices assumed, the FABM 1 pavements are between 80 and 90% the cost. It is emphasized, that this is likely to be a conservative position with recent prices in London suggesting that FABM 1 may be 40% the price of asphalt rather than 50%.

8. Energy and carbon content considerations

In considering the energy and carbon content of FABM and other pavement materials, and then to compare pavement structures employing FABM with other pavements, it is necessary to agree robust data for these aspects. This is a complicated and controversial business not helped by the fact that much of the currently accepted data in circulation, even that used by learned and government bodies such as ICE, the EA, WRAP, Bath University and the TRL, has been provided by industry.

In addition, transport is a highly significant part of any comparison and the location of a mixture production facility relative to constituent sources and then to the place of use of the mixture, can swamp any benefit of using say by-products, which in such cases can have little impact when considering carbon and energy.

The complexity of the situation is clear when the 'life-cycle flowchart' of a pavement shown in figure 2 is considered.

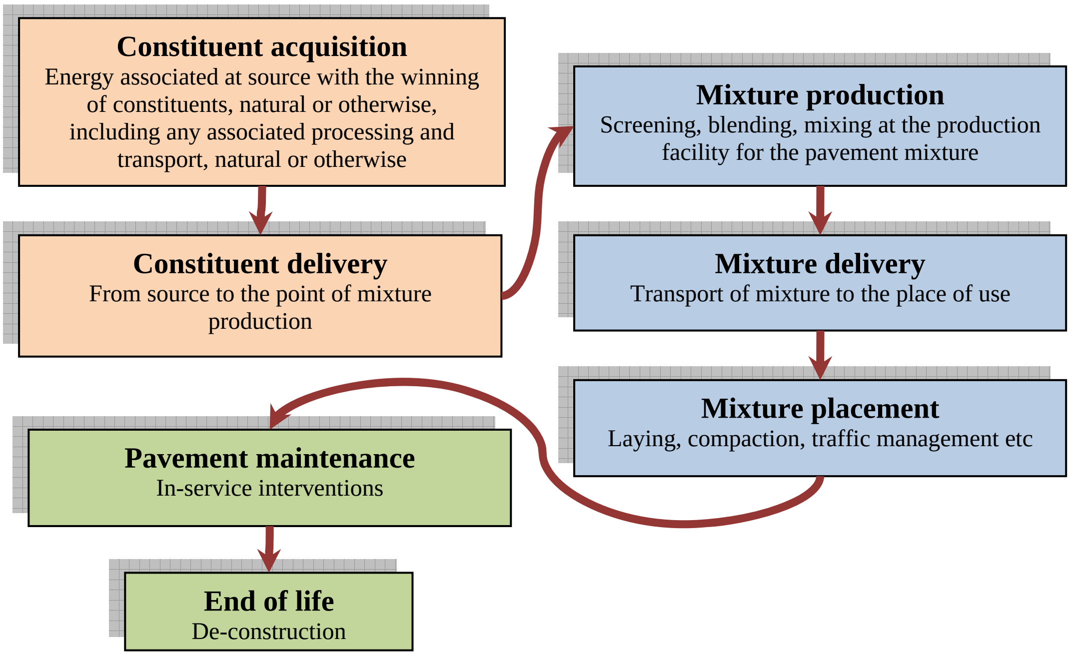

Figure 2: A flow chart of the life cycle stages of a pavement

The matter if further complicated by the various pavement design methods that may be used for the various pavement types as well as the various maintenance scenarios that may be employed. There is also of course, the debate on the amount of recycled material that may be acceptable in products such as a bituminous mixture without effecting durability and performance.

Understandably, there can be extreme variations in this data, which therefore can make any meaningful comparison meaningless. Nevertheless this paper will try to present meaningful data, including transportation of the constituent materials to the mixing plant, but excluding haulage from the mixing plant to site.

9. Embodied CO_2 (eCO_2) and energy of constituents

The production of fly ash involves little activity post extraction from the flue gases within the power station. The dry ash is often collected from the hoppers immediately below the electrostatic precipitators and can be used dry in FABM/SFA production. Such fly ash has an effective eCO_2 and energy value of NIL. However, as transportation of dry fly ash requires hermetically sealed tankers with appropriate receiving silo on site, it is common-place to 'condition' the ash with water and deliver it in sheeted tipping vehicles as would normally be used for aggregates. This is usual for FABM production and additionally reduces environmental impacts.

To condition one tonne of fly ash requires typically 1 kWh of electrical energy and 150kg of water. Using a standard UK figure of eCO_2 for electricity of 0.547 kg of CO_2 per kWh, this equates to 0.588 kg of CO_2 per tonne of conditioned fly ash. In addition, particularly with older stockpiled conditioned ash, it may be necessary to process the ash, by screening, to reduce the size of lumps of fly ash. This requires a further 1kWH of energy and thus the total eCO_2 of conditioned fly ash for FABM will be 1.13 kg per tonne.

The energy consumption and eCO_2 of fly ash and other pavement material constituents used within the calculations for this paper are shown in Table 6. These are based on published data drawn from a number of sources; these are detailed in Appendix A.

Table 6: Energy consumption and eCO_2 of pavement material constituents

Material	Energy consumption at the point of sale in MJ/tonne (kWh/tonne)	eCO2 kg/tonne
Conditioned fly ash	7.2 (2.0)	1.13
Lime	4,378 (1,216)	766
Bitumen	630 (175)	380
Crushed rock	44 (12.2)	6.2
Recycled aggregate	32 (8.9)	3.5

As seen with the various sources of data within Appendix A, there is considerable variation in values for some materials. Of particular concern are the figures for bitumen with embodied energy values being quoted ranging from 173 to 53,430 MJ/t and eCO_2 ranging from 95 to 1,179 kg eCO_2/t. Conservative figures of 630MJ/t for embodied energy and 380 kg eCO_2/t have been used. In respect of lime, there is little clarity within the various references whether hydrated lime or quick lime is being quoted. Inherently, due to the chemistry of the two materials the eCO_2 figure and embodied energy data will be significantly different from each other. For the purposes of this paper, hydrated lime has been assumed.

10. Embodied CO_2 (eCO_2) and energy of production, transport, and construction

In order to establish the embodied energy and eCO_2 of pavement mixtures at the gate and even in the finished place of use, it is necessary to consider production methods, transport and construction. In the case of FABM and SFA, production can be carried out in either a central production facility as is the case for bituminous mixtures or in-situ using mix-in-place construction.

For the ease of mixture and pavement considerations in this paper, comparison will be limited to mixture production in a central facility. This is mainly for simplicity purposes but with the advent of central hub recycling plants, is perhaps opportune.

It should not be forgotten however that with in-situ treatment, with considerably less emphasis on transport of materials, just limited in fact to the binder, and no transport of the mixture, the energy and carbon benefits are hard, although frequently, to ignore. That in-situ treatment can be utilised for both new build and pavement rehabilitation work should never be forgotten and always considered as part of any pavement works. The additional fact that the process can be used to convert even very cohesive soils into material of sub-base quality, it is without a shadow of a doubt the most effective process the pavement engineer has at his disposal for energy and carbon minimisation. It also then releases recycled material from their wasteful use in unbound capping and sub-base for their proper application as aggregate for bases.

The carbon and energy for production, transport and construction are shown in table 7. Calculations of eCO_2 were based on DEFRA Guideline data for haulage of Rigid (>17t) and Articulated (>33t) vehicles as appropriate. As previously stated all the data is drawn where possible from published data and the sources have been acknowledged.

Table 7: Energy consumption and eCO_2 of production & transport

Operation	Energy consumption at point of sale in MJ/tonne (kWh/tonne)	kg eCO_2/tonne
Hot-mix	Range of 250 – 400 > 300 used (70 –110 > 83.3)	26.4 used Converted from energy, assumed 90% fuel oil and 10% electricity
Cold-mix	Range of 36 to 70 > 50 used (13.9)	7.6 used
Rigid vehicle >17t (DEFRA data for 2009) NB: Includes an allowance for back haul		0.17797 kg of CO_2 per tonne.km
Artic >33t (DEFRA data for 2009) NB: Includes an allowance for back haul		0.08237 kg of CO_2 per tonne.km

11. Embodied CO_2 (eCO_2) and energy of pavement mixtures

Table 8 includes the embodied carbon and energy for mixtures at the exit gate of the production facility. The Table also includes the energy consumption of the constituent materials. It assumes transportation distances excluding return journeys, which are assumed within the DEFRA figure, as appropriate of;

- 100km for fly ash and lime
- 125km for bitumen
- 50km for crushed rock aggregates
- 50km for recycled aggregate

Where available, this again is drawn from published data and the sources acknowledged. Where not, guestimates are included with reasoning, this then permits mixture-to-mixture comparison.

Table 8: Energy consumption and eCO_2 of pavement mixtures

Material	Energy consumption at point of sale in MJ/tonne (kWh/tonne)	eCO2 kg/tonne at the point of sale
TSC (Thin surface course)	501 (139)	63.4
DBM50 (50% recycled)	485 (135)	55.9
FABM 1 (100% recycled)	301 (84)	40.2

Lack of space does not permit inclusion of the spreadsheets used to derive the figures in table 8. If it did, the spreadsheets would show that mixing contributes about 50% of the carbon & energy figures for asphalt base but just 15% for FABM. The main contributor to the FABM figures is lime at about 50% for both energy and carbon. These percentages are not surprising when one considers the difference between hot and cold-mix and how lime is produced.

When however the bitumen input for DBM base is considered, the picture is confusing with bitumen contributing 30% to the carbon figure but just 5% to the energy figure. Since carbon and energy are related, this suggests discrepancies in the data used here. Quite whether this originates at the carbon or the energy end is not currently clear, but when one considers the wide range of carbon and energy figures quoted for bitumen (discussed in section 9), it is obvious that this is an area that needs further investigation and agreement.

12. Embodied CO_2 (eCO_2) and energy of pavements

Using the data from Table 8, which includes transport of materials to the mixing depot, the mixing and the embodied energy/CO_2 inherent to the material, it is possible to compare the eCO_2 content of FABM 1 and asphalt pavements on a foundation class 2, i.e. Type 1 sub-base, as shown in Table 5. This is illustrated in Table 9 using FABM 1 containing 100% recycled material as is the norm and DBM containing the maximum currently permitted, 50% recycled aggregate, and 0% recycled. The comparison in Table 9, and the one later in Table 11, assumes a compacted density of 2.4 T/m3 for asphalt and 2.05 T/m3 for FABM 1.

Table 9: eCO_2 comparison of FABM1 and DBM50 pavements in Table 3

Road Designation	Asphalt Option (No recycled)	Asphalt Option (50% recycled)	FABM Option (100% recycled)
	kg of eCO_2 per square m of road		
HAUC Type 4 roads (up to 0.5 msa) on foundation class 2, i.e. On Type 1 sub-base	28.0	27.6	26.5
HAUC Type 3 roads (0.5 to 2.5 msa) on foundation class 2, i.e. On Type 1 sub-base	30.8	30.2	26.5
HAUC Type 2 road (2.5 to 10 msa) on foundation class 2, i.e. On Type 1 sub-base	37.7	36.9	33.5
HAUC Type 1 road (10 to 30 msa) on foundation class 2, i.e. On Type 1 sub-base	43.1	42.3	37.8

From Table 9, it can be seen that FABM pavements have some 86 to 95% the eCO_2 of asphalt pavements based on DBM 50 as shown in Table 10.

Table 10: eCO_2 as percentage of Asphalt option

Road Designation	Asphalt Option (No recycled)	Asphalt Option (50% recycled)	FABM Option (100% recycled)
	% eCO_2 of Asphalt Option (No recycled)		
HAUC Type 4 roads (up to 0.5 msa) on foundation class 2, i.e. On Type 1 sub-base	100.0%	98.3%	94.5%
HAUC Type 3 roads (0.5 to 2.5 msa) on foundation class 2, i.e. On Type 1 sub-base	100.0%	98.2%	86.1%
HAUC Type 2 road (2.5 to 10 msa) on foundation class 2, i.e. On Type 1 sub-base	100.0%	98.1%	89.0%
HAUC Type 1 road (10 to 30 msa) on foundation class 2, i.e. On Type 1 sub-base	100.0%	98.1%	87.7%

Similar comparisons can be carried out with energy but since energy is part of the eCO_2 calculation it can be considered, in some quarters, academic. However the conference is referred to an ETSU publication from 1997 that was prepared by one of the authors (Ref 6). This concluded that the 4 main areas for considerable potential to reduce energy consumption were;

- reducing haulage through the use of local materials and or in-situ recycling or stabilisation
- use of binders based on slag and coal fly ash
- use of cold mixing for bituminous mixtures
- use of self-cementing products like crushed concrete and air-cooled slag mixtures.

These conclusions although now self-evident have, despite the fact they were published 12 years ago, yet to be universally accepted and acted upon in the UK, so this paper makes no apologies for repeating the energy benefits of FABM here.

Using the energy consumption data shown in the above Tables, the energy benefits of FABM pavements compared in Table 5 to asphalt pavements are shown in Table 11.

Table 11: Comparison of energy consumption for FABM1 and DBM50

Road Designation	Asphalt Option (No recycled)	Asphalt Option (50% recycled)	FABM Option (100% recycled)
	Embodied Energy - MJ per square metre		
HAUC Type 4 roads (up to 0.5 msa) on foundation class 2, i.e. On Type 1 sub-base	236.6	234.3	210.5
HAUC Type 3 roads (0.5 to 2.5 msa) on foundation class 2, i.e. On Type 1 sub-base	260.2	257.6	210.5
HAUC Type 2 road (2.5 to 10 msa) on foundation class 2, i.e. On Type 1 sub-base	319.1	315.8	269.4
HAUC Type 1 road (10 to 30 msa) on foundation class 2, i.e. On Type 1 sub-base	366.2	362.4	305.0

Thus, as with eCO_2, fly ash or binders based on fly ash are beneficial with the energy consumption of a FABM 1 pavement between 84 and 90% of the energy consumption of the asphalt (50% recycled) option.

13. Discussion

Any paper such as this is by definition out of date as soon as it written. Carbon and energy data is constantly evolving as is technology with pavement materials, their mixture design, thickness design and production.

Taking carbon and energy, it is apparent looking at the wide variation with values from different sources, particularly it must be said with bitumen and asphalt, that consensus and not just industry consensus needs to be reached and urgently. Without this, comparisons as presented in this paper are meaningless.

Considering technology, cold-mix and warm-mix processing for asphalt is evolving as we speak. Some of this evolution involves the use of bitumen emulsion or foamed bitumen. It also, interestingly, involves the use of fly ash with either lime or cement. Whether we then have a bituminous or a hydraulically bound mixture is debatable but whatever, it will alter the carbon and energy scenario for asphalt.

With FABM, the primary contributor to their carbon and energy footprint is lime. However this can be reduced; for example, by reducing the lime content currently used. Research shows that the 3% lime currently used in FABM 1 could be reduced to 1.5% without any change in performance. There are also other sources of alkali, including waste alkalis, that could be investigated to complete the hydraulic equation for fly ash in FABM, and reduce their environmental footprint.

These technology changes will also affect costs and possibly recycled contents for both asphalt and FABM.

It can also be argued, in the overall scheme of things, why are we even considering the carbon and energy for pavement construction. Compared to the vehicles that use the pavement, their manufacture and the fuel they use, particularly for road pavements, the road construction and maintenance contribution is negligible. However it can also be argued that every little helps.

14. Conclusions

The performance of FABM 1 is proven and not in doubt. This paper shows also that with the data presented and used, its environmental credentials are equally impressive. For any authority keen to reduce their dependency on primary products and to use more environmentally acceptable yet proven processes, this paper illustrates that FABM pavements are an answer, and an economic answer at that.

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Appendix A – Reference Sources and Values for Calculation of Energy and CO_2

Source	Conversion factors	Values
Conversion factors used in calculations		
MJ to kWh	MJ ÷ 3.6 = kWh	3.6 MJ/kWh
Conversion from MJ/t to kg eCO_2/t for grid electricity	÷3.6 (kWh) x 0.54667 (DEFRA, grid electricity value, Table 3c)	kg eCO_2 = MJ x 0.15185
Gas oil conversion Used for conversion of hot mix heating to embodied energy	3.0389 kg CO_2/litre (DEFRA)	0.29108 kg eCO_2/kWh
Diesel conversion Used to convert transport data to embodied energy	kWh x 0.26630 = kg eCO_2 MJ / 3.6 x 0.26630 = kg eCO_2 (DEFRA, Table 1b)	MJ = kg eCO_2 / 0.07397 = MJ = kg eCO_2 x 13.519

Bitumen		
Source	**Comment**	**Values**
ASPECT V1 database	Eurobitume figure quoted	280 kg eCO_2/t
Eurobitume	Energy consumption	4,710 MJ/t
Bath Carbon Inventory Comment made about poor data availability and data range. Cradle to gate.	Average embodied energy Selected EE value used eCO2 value used	17.91MJ/kg 47MJ/kg = 47,000MJ/t 480 kg eCO_2/t
ASPO Annual Meeting	Range given for the extraction of crude from the ground.	1,179 to 464 kg eCO_2/t
WRAP Carbon Estimator	Embodied energy (elec.) Figure for overall CO_2 not found	173MJ/t > 26.2 kg eCO_2/t
Energy Efficiency Demonstration Scheme	Energy consumption at point of sale.	630MJ/t = 95 kg eCO_2/t (assumed elec.)
CIMBETON (Oekoinventare)	Energy consumption eCO_2	53,420 MJ/t 504kg/t
	Value used in calculations	**380 kg eCO_2/t** **630 MJ/t** **Embodied energy**

Crushed Rock Aggregates		
Source	**Comment**	**Values**
Energy Efficiency Demonstration Scheme	Energy consumption at point of sale.	50MJ/t > 50 x 0.15158 = 7.5 kg eCO_2/t
WRAP Carbon Estimator	Energy Diesel (WRAP) Energy crushing (WRAP)	16.99MJ/t > 16.99/3.6 x 0.27652 = 1.305 kg eCO_2/t 21.19MJ/t > 21.19/3.6 x 0.27652 = 1.678 kg eCO_2/t Total = 2.983 kg eCO_2/t
EA Construction Carbon Calculator 2007 (V3)	CO_2 emissions	5 kg eCO_2/t
USIRF	Energy consumption	56 MJ/t
CIMBETON (Oekoinventare)	Energy consumption eCO_2	189 MJ/t 10.3kg/t
	Value used in calculations	**6.16 kg eCO_2/t** **44.1 MJ/t Embodied energy**

Recycled Aggregates		
Source	**Comment**	**Values**
WRAP Carbon Estimator	Energy Diesel (WRAP) Energy crushing (WRAP)	16.99MJ/t > 16.99/3.6 x 0.27652 = 1.305 kg eCO_2/t 21.19MJ/t > 21.19/3.6 x 0.27652 = 1.678 kg eCO_2/t Total = 38.2 MJ/t & 2.983 kg eCO_2/t
EEBPP (GIR No 49)	Assumed	25 MJ/t > 25 x 0.15185 = 3.8 kg eCO_2/t
EA Construction Carbon Calculator 2007	CO_2 emissions AggRegain CO_2 estimator (2006)	3.69 kg eCO_2/t
	Value used in calculations	**3.5 kg eCO_2/t** **31.6 MJ/t Embodied energy**

Lime (Hydrated lime assumed)		
Source	**Comment**	**Values**
EEBPP (Gir No.49)	Energy consumption at point of sale (Elec. assumed)	5,000 MJ/t > 5000 x 0.15185 = 759 kg eCO_2/t
WRAP	Embodied energy CO_2 emissions	2,836.8 MJ/t 800 kg eCO_2/t
Bath	Embodied energy CO_2 emissions	Range 40 to 10,240 Used 5,300 MJ/t 740 kg eCO_2/t
EA Construction Carbon Calculator 2007	CO_2 emissions ICE Carbon Inventory 2006 (Bath)	1,580 kg eCO_2/t
	Value used in calculations	**766 kg eCO_2/t** **4,378 MJ/t Embodied energy**

Other materials		
Material	**Comment**	**Values**
Water	DEFRA Guideline values Sept 2009	276 kg eCO_2/million litres > **0.276 kg eCO_2/t**
Conditioned fly ash	UKQAA data 1 kWh to condition ash + 1 kWh to screen ash = 2kWh plus 150l water	2*0.54667 + 150/1000 x 0.276 = **1.13 kg eCO_2/t** **7.2 MJ/t Embodied energy**
Hot-mix energy consumption	ETSU 300 MJ/t, Cimbeton 250 MJ/t, Hanson 250-400 MJ/t	Figure used **300 MJ/t**
Cold-mix	ETSU 70 MJ/t, Cimbeton 36 MJ/t	Figure used **50 MJ/t**

Transport – standard		
Material	**Distance in kms One way – return assumed in conversion factor**	**Mode of transport**
Fly Ash	100	Artic
Lime	100	Artic
Bitumen	125	Artic
Sand and Gravel	50	Rigid
Crushed Rock Aggregates	50	Rigid
Recycled aggregates	20	Rigid
Delivery from mixer to site	0	Excluded
Rigid vehicle >17t (DEFRA data) NB: Includes back haul. Annex 7 Table 7e	0.17996 kg of CO_2 per tonne.km	
Artic >33t (DEFRA data) NB: Includes back haul. Annex 7 Table 7e	0.08340 kg of CO_2 per tonne.km	

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