

Environmental and financial costs and benefits of warm asphalts

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Abbreviations and acronyms

HMA Hot mix asphalt

KGO Karl Gunnar Ohlson-III

LEA Low energy asphalt

WAM Warm asphalt mix

or

WMA Warm mix asphalt

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Executive summary

Warm asphalts are asphalts produced at significantly lower temperatures than the approximately 160°C used at a hot mix plant. Depending on the technology used, laying and compaction may also be possible at significantly reduced temperatures.

The technologies are based on at least one of the following five principles:

- 1 Modification of the asphalt mixing process (without changing the mix components). Significant plant modifications are necessary. Paving is completed at similar temperatures as for standard mixes for compaction.
- 2 Addition of substances which decrease the viscosity of the bitumen in the high temperature region. Various waxes are used to enable mixing at reduced temperatures. Below the wax's softening range the binder is harder than the original bitumen, and paving cannot be carried out at reduced temperatures; alternatively it may be appropriate to use a softer grade of bitumen. Minor plant adjustment to allow addition of the wax in controlled amounts may be necessary.
- 3 Modification of the bitumen-aggregate interaction. Proprietary chemical additives have been developed which improve the mix workability and aggregate coating without changing the bitumen viscosity significantly. Mixing and paving can both be carried out at significantly reduced temperatures. The effectiveness of the additives may vary from bitumen to bitumen and aggregate to aggregate. Apart from apparatus to inject the additive into the bitumen, no plant modification is needed.
- 4 Introduction of water to foam the bitumen. This may be achieved by:
 - a) foaming of bitumen in the asphalt plant before application to heated aggregate. Modified or specialised plant is required
 - b) use of zeolite additives which slowly release water above 100°C
 - c) addition of a warm bitumen emulsion (at approximately 90°C) to heated aggregate. Energy savings may be minimal or even negative for this process, owing to the need to manufacture the emulsion. However, paving at significantly reduced temperature is possible
 - d) addition of water to a finer part of the aggregate to promote foaming when the bitumen is added. This process allows both mixing and paving to be carried out at significantly reduced temperatures, and is classified as 'half warm' rather than simply 'warm'. Considerable plant modification may be necessary, and a significant royalty payment is required when setting up
- 5 Use of low viscosity vegetable binder. No published material on the effectiveness or behaviour of these products was available at the time this report was prepared.

Details are supplied in this report for examples of the first four of these technologies, and typical values calculated for the energy needed to produce a tonne of mix.

Published results for fuel and electricity consumption of the hot mix process indicate that the energy expended in heating the aggregate and bitumen (approximately 277MJ/tonne of mix) is around 44% of the total energy involved in production, transport, laying and rolling of asphalt. This places an upper limit on the proportion of energy expended that can be saved by adopting a warm asphalt manufacturing process.

Apart from the warm emulsion-based asphalt, the calculated heating energy expenditures are less than reported results. The differences may reflect, at least partly, unavoidable inefficiencies and losses.

However, there may be considerable opportunity for significant energy savings by maximising efficiency through good insulation, burner adjustment and covering aggregate to minimise moisture content.

Measured data are not available for all processes, and so for comparative purposes it is necessary to use calculated figures. These indicate that many processes have the potential to give heating energy savings of the order of 20%; the anhydrous chemical additives may give somewhat better savings than this, while the half warm processes can give around double this figure. The situation with the hot emulsion-based process is not clear, but it is likely that the energy savings of manufacture at reduced temperatures are negated by the energy expended in manufacturing the emulsion.

The lower manufacturing temperatures will result in reduced emissions of carbon dioxide and other organic gases. A typical warm asphalt process would, if universally adopted throughout New Zealand, result in an annual reduction of CO₂ equivalent emissions of approximately 4700 tonnes. The low energy asphalt (LEA) half-warm process would roughly double this, but adoption of this process may not be financially justifiable for some asphalt producers, because of the cost of the necessary plant refurbishment.

Currently the balance of savings and costs of warm mix technology results in warm mixes being more expensive than the equivalent standard hot mixes.

As a rule asphalts produced by warm mix processes have comparable resistances to moisture (despite the frequent use of water for foaming) and resilient moduli. Improved workability of the warm and half-warm products can result in a higher compacted density being achieved, resulting in reduced long-term hardening, less opportunity for water penetration, and reduced susceptibility to rutting.

Asphalt lifetimes may be affected by the hardness of the binder at ambient temperatures. Apart from reduced hardening due to the lower processing temperatures, there will be increases in some cases where additives are used, in particular for organic waxes and, to a lesser extent, zeolites.

The principal advantages of warm asphalt technology are claimed to be:

- reduced heating fuel requirements
- reduced carbon dioxide, other greenhouse gases and volatile organic compounds emissions
- increased time available for transport, laying and compaction
- ability to pave satisfactorily at lower ambient temperatures. This is the case only for certain technologies
- increased safety for operators
- longer surface life due to decreased binder oxidation and improved compaction.

Possible disadvantages may include:

- an increased susceptibility to stripping proposed due to residual water resulting from foaming and/or lower mixing/compaction temperatures (Button et al 2007, p37). No conclusive evidence has been reported for this to date
- higher susceptibility to rutting due to the binders not being so hardened by the manufacturing process (controllable by using a harder binder)
- greater expense from additives, plant modification and purchase of patent rights.

In New Zealand, Fulton Hogan Ltd. and Downer EDi Works Ltd possess plant capable of producing warm asphalt mixtures.

Manufacturing warm mixes currently costs more than for hot mixes, although the anticipated increases in energy costs will probably change this situation.

At this stage in the development of the technologies none appear to be especially suited to New Zealand conditions. Environmental advantages due to reduced fuel consumption will need to be balanced against costs of additives and modifying plant and the varying maturity of the different technologies. Consequently no recommendation covering all cases can be made at present.

Procedures for laboratory design of warm and half-warm mixes appear to be still in the developmental stage. Watching briefs are recommended in particular for

- use and innovation with the LEA and anhydrous chemical additives processes
- the development of quality control procedures and specifications
- information on the long-term pavement performances obtained with the various technologies.

Present indications are that warm and half-warm mixes can be produced that have similar performance to hot mixes, and provision should be made to be ready to adopt these technologies for the state highway network through suitable quality control procedures. At present asphalt quality control is usually carried out in accordance with TNZ M/10: 'Specification for asphaltic concrete' (Transit NZ 2005a). The mix design method specified in this standard is inappropriate for warm asphalts; to continue with the M/10 approach a different method for each warm mix technology would be needed. It is therefore recommended that an alternative development of a performance-based specification for asphalt, currently TNZ P/23 (Transit NZ 2005b), be accelerated. This type of specification is primarily based on the ultimate properties of the finished pavement and is theoretically suitable for all mix processes.

In terms of emissions from the asphalt production industry, warm and half-warm technologies have the potential to make a significant reduction to CO₂ emissions. However, given the total CO₂ equivalent emissions for New Zealand, this needs to be accompanied by a wide variety of other emission control strategies.

Abstract

Warm asphalts are asphalts produced at significantly lower temperatures than the approximately 160°C that is typical of a hot mix plant. Depending on the technology used, laying and compaction may also be possible at significantly reduced temperatures. The report gives a summary of current warm asphalt technologies, followed by details of costs, temperature reductions and energy savings. A comparison is made of potential environmental costs and benefits of hot mix manufacture and the different warm mix methodologies.

1 Introduction

1.1 Background

Approximately 1 million tonnes of asphalt are produced annually in New Zealand as hot mixes (pers comm, Alan Stevens, Roading New Zealand, October 2008). Production involves considerable fuel and energy consumption and emission of greenhouse gases (especially carbon dioxide). Production at lower temperatures, if feasible, has the potential to use less fuel, resulting in reduced costs and lower emissions.

One way of achieving these ends lies in use of 'cold asphalts', which are produced with bitumen emulsions instead of hot bitumen. The technology has been long established overseas, but there has been an ongoing problem getting adequate mix compaction, and the construction method is usually only used for lightly trafficked roads. In addition, there is an environmental danger of emulsion runoff (Ball et al 2008).

An alternative is to use warm asphalts, which are designed to be produced, and sometimes placed and compacted, at lower temperatures than hot mix. They have been produced overseas since the early 1990s, although new methods of manufacture are continually being developed. Warm mixes do not have the same compaction problems as cold mixes. Energy savings vary with the particular technology used; in one case a reduction in carbon footprint of over 50% has been claimed. Most procedures involve modifying, temporarily or permanently, the bitumen binder used to produce the asphalt, so that it has a reduced viscosity at production and compaction temperatures but is substantially unchanged at normal road temperatures. In other instances the bitumen-aggregate bonding is adjusted chemically so that satisfactory compaction at reduced temperatures is achieved. A number of processes and/or additives are available to achieve these effects.

1.2 Purposes of the study

This report summarises developments in warm asphalt manufacture up to 2009, and has the following objectives:

- Summarise research and trials carried out overseas and in New Zealand with the various methods of producing asphalt mixes.
- Evaluate as far as possible energy consumption and emissions for each method, and compare these with each other and the figures for hot mix production.
- Compare costs of setting up and production.
- Investigate if any particular methodologies are particularly suited to the New Zealand situation.
- Establish whether technologies are at a stage where they can contribute significantly to environmental enhancement in New Zealand; whether local research and trials are needed; and whether steps should be taken to adopt the technology.

2 Summary of methodologies

2.1 Introduction and current reviews of practice

The technologies are based on at least one of the following five principles:

- 1 Modification of the asphalt mixing process (without changing the mix components)
- 2 Addition of substances which decrease the viscosity of the bitumen in the high-temperature region
- 3 Modification of the bitumen-aggregate interaction
- 4 Introduction of water to foam the bitumen
- 5 Use of low-viscosity vegetable binder.

Several extensive discussions of the various methodologies have recently been published, principally in the United States to familiarise practitioners with recent European developments (Hurley and Prowell 2006a; Button et al 2007; D'Angelo et al 2008; Button and Chowdhury 2008). The last three of these discussions can, at the time of writing, be accessed through the internet (see under References).

The five different technologies are described below.

2.2 Modification of the asphalt mixing process

2.2.1 Karl Gunnar Ohlson-III (KGO) or 'addition sequence' process

This process was developed in Sweden. The hot coarse aggregates (>4mm sieve size) are blended with the bitumen. The increased binder-aggregates ratio means the mixing can be done at a slightly reduced temperature. The hot filler material (<0.063mm) is then added and dispersed into the precoated mix in a controlled way, followed by the fines (0.063–4mm) (Viman et al 2008)

2.2.2 Two-phase mixing process (Shell warm asphalt mix (WAM) foam process)

Aggregates are mixed with a soft (penetration 160 to 400) bitumen at a (consequently) reduced temperature. A harder bitumen (penetration 35 to 100) is then foamed and added and mixed at the reduced temperature. This methodology can also be classified as a foam-based method (see section 2.5.1.1). A surfactant may be added to aid in the foaming of certain bitumens (Larsen et al 2004) and an antistripping agent may be added to the softer bitumen. Kolo Veidekke and Shell possess the WAM foam patent rights worldwide except in the USA where BP has the patent.

2.2.3 General comment

Plant modifications are necessary in both cases. Paving is completed at similar temperatures as for standard mixes for compaction, so that the time available for transport, laying and rolling is unchanged.

2.3 Viscosity reducing organic additives

Montan wax, amide wax or Fischer-Tropsch wax is added to the bitumen, typically around 1.5%, either as solids into the asphalt mixing plant or in a pre-blended binder. The wax melts over a temperature range around 100°C, giving a reduced viscosity product which can be blended with hot aggregate at a reduced temperature, typically around 130°C to 140°C. Compaction must take place at temperatures above the wax's melting region. While the wax decreases the binder viscosity at higher temperatures, at ambient

temperatures, where the wax has crystallised, the binder is harder than the original bitumen. To some extent this effect is countered by the reduction of oxidation of the bitumen during the manufacturing process.

Examples of wax additives are Sasobit® (Fischer-Tropsch wax) (Hurley and Prowell 2005a), Ecoflex (Colas proprietary product), Licomont BS 100 (fatty acid amide) and Asphaltan B (Montan wax).

2.4 Low dosage anhydrous chemical additives

Some proprietary chemical additives have been developed which improve the mix workability and aggregate coating without changing the bitumen viscosity significantly. Mixing can take place around 120°C and compaction down to 90°C. Additive dosages of around 0.2% to 0.5% by weight of the bitumen are typical. Minimal plant modification is needed for adding the chemical to the bitumen.

Examples of these additives are REVIX (a liquid produced by Mathy Technology and Engineering Services Inc and Paragon Technical Services Inc, USA), Cecabase RT (liquid) and Akzo Rediset™ WMX (solid pastilles). There is some evidence that the improved compaction is associated with the interaction at the aggregate binder interface (Grampre et al 2008), so effectiveness of the method may vary from aggregate to aggregate and/or from one bitumen to another of the same grade.

2.5 Technologies based on introduction of water to foam the bitumen

2.5.1 Warm technologies (>100°C)

2.5.1.1 WAM foam process

(See section 2.2.2 for a fuller discussion.) Dry aggregates are coated with a soft binder (penetration 160 to 400) and water is then introduced with a harder bitumen (penetration 35 to 100) to produce foam.

2.5.1.2 Zeolite additives

These are added as part of the filler component. For suitable zeolites the structure contains around 21% by weight of water in small pores which is released over several hours upon heating. The softening effect operates as long as the asphalt is above 100°C.

Examples are Aspha-Min® (Hurley and Prowell 2005b) dosed at approximately 0.3% by mix weight, and Advera WMA (PQ Corporation, USA) (~0.25% by mix weight).

2.5.2 Half-warm technologies (<100°C)

2.5.2.1 Emulsion-based mixes

Bitumen emulsion (~30% water content) at approximately 90°C is added to hot dry aggregate. Most of the water is vaporised and the mix is compacted below 100°C.

Evotherm (Hurley and Prowell 2006b) is currently promoted in the USA.

2.5.2.2 Foam mixes

Foamed bitumen is mixed with warm or half-warm aggregates. A hygroscopic filler (0.5 to 1.0%) may be added to maintain workability. Energy savings of 30% to 50% have been claimed; however, some research has questioned the quality of the product (Gaudefroy et al 2008).

Examples of these products are LT Asphalt (Netherlands and Italy) and the Astec Double-Barrel® Green and Terex® WMA systems (USA). Plant modification is needed to allow water injection in order to foam the asphalt binder before it contacts the aggregates. Antistripping agent may be added. Downer EDi Works (New Zealand) and Fulton Hogan Australia (2009) employ the Astec process.

2.5.2.3 Low energy asphalt (LEA) processes

Bitumen is added to a portion of the aggregate mix which is at a lower temperature than for hot mix and contains some water. The spontaneous foaming and expansion of the bitumen leads to a thicker binder around the aggregate. Mixtures are workable from 95°C down to around 60°C (Hayward and Pidwerbesky 2009), allowing a longer time, compared with standard hot mix, to transport and lay the asphalt.

There are at least three different sequences employed for mixing coarse aggregate, fines, water and bitumen (Olard, le Noan et al 2008).

With representative temperatures, these are:

Process A: Heat the large aggregate (~65% of aggregate fraction) to 130°C
 Add bitumen (170°C)
 Add the cold moist fine fraction to induce foaming

Process B: Heat the large aggregate to 130°C
 Add the cold moist fine fraction
 To the mixed aggregate (at approximately 95°C) add any extra water needed
 Add bitumen (170°C)

Process C: Heat all the aggregate to 100°C
 Add any extra water needed
 Add bitumen (170°C)

Some proprietary additives are needed to ensure the asphalts are not susceptible to water damage. In New Zealand Fulton Hogan has adopted this process to produce Coolpave®, and has laid mixes in Auckland, Christchurch and Dunedin and at Christchurch airport (Pidwerbesky and McDonald 2008; Hayward and Pidwerbesky 2009).

2.5.3 Low-viscosity plant-based binders

Some bitumen substitutes derived from plant or tree material have been developed which allow mixing and paving around 130°C (Olard, Héritier and Beduneau et al 2008). As yet it is uneconomic to produce these materials on a large scale. No published information on trials with these materials has been found.

2.6 Mixing and paving temperatures

Figures taken from the literature are shown in table 2.1.

Table 2.1 Mixing and minimum paving temperature for different mix processes

Production method		Typical mixing temperature °C	Typical paving temperature °C
Standard hot mix		160	135 ⁴
KGO-III		130 ²	110(estimate)
WAM foam process		110□120 ³	110 ³
Viscosity reducing organic additives		135 ¹	Not available
Low dosage anhydrous additives		110□120 ⁴	90 ⁴
Zeolite additives		130 ⁹	100+ ⁹
Hot emulsion based		135 ⁶	110□120 ⁶
Foam mix	Typical	135 ⁷	110+ ⁷
	Double Barrel Green	110□140 ⁵	110□140 ⁵
LEA processes A & B		130 ⁸	85 ⁸
LEA process C		100 ⁸	85 ⁸

¹Olard, H ritier and Beduneau 2008, ²Viman et al 2008, ³Larsen et al 2004, ⁴Grampre et al 2008, ⁵Fulton Hogan Australia 2009, ⁶(Aggregate temperature) Hurley and Prowell 2006b, ⁷EAPA 2009, ⁸Olard, le Noan et al 2008, ⁹Hurley and Prowell 2005b

Mixing temperatures has a major effect on the amount of energy required to heat the asphalt materials (see chapter 3). The low dosage anhydrous additives and LEA processes allow paving at significantly lower temperatures than the other processes, and may therefore be preferred choices if frequent paving at low ambient temperatures is required or asphalt has to be conveyed long distances from the plant.

3 Energy costs and savings

3.1 Energy inputs for a standard hot mix

To establish a point for comparing the energy expenditures for warm and half-warm asphalt mixes we require an estimation of the amount of energy expended in producing a given amount of hot mix. Patrick and Arampamoothy (2009), quoting Hawthorne (1975), list some typical energy equivalences for various components of the asphalt manufacturing process (table 3.1):

Table 3.1 Energy required to produce given quantities of various construction materials

Material or process	Energy expenditure
Petrol	34.8MJ/l
Kerosene	37.6MJ/l
Diesel	38.7MJ/l
Bitumen	700MJ/t
64% emulsion	585kJ/l
Crushed aggregate	80MJ/t
Hot mix manufacture	478MJ/t
Hot mix laying and compaction	56MJ/t
Basecourse laying and compaction	65.8MJ/t
Cartage (return trip)	2.7MJ/t/km

Difficulties arise in comparing such results with those for other asphalt manufacturing processes. First, a wide range of results have been published. Patrick and Arampamoothy (2009) cite published values for hot mix manufacture ranging from 23.0 to 3400MJ/tonne mix. A probable major reason for this wide spread of figures could be that different publications include or exclude different factors, such as energy for plant operation, energy to manufacture bitumen, removal of water from aggregate, and transport of material to the manufacturing plant, in their estimates. Plant operation will typically require a considerable amount of electrical energy. Other factors will enter in, such as the effectiveness of plant insulation and adjustment of the burner flame for full efficiency.

3.2 Comparison of production process energy inputs

Kristjansdottir et al (2007) and Olard, Héritier and Beduneau (2008) published details of energy input calculations for a typical hot mix and mixes with the same aggregate grading manufactured by three versions of the LEA processes (see section 2.5.2.3). The same methodology will be used to compare energy inputs for different energy saving processes. For this purpose, the specific heats of the various components are required. Different aggregates and bitumens have different specific heats, and specific heats of water and bitumen vary with temperature. Representative values will be used (table 3.2).

Table 3.2 Representative specific heats of asphalt components

Material	Notation	Specific heat $\text{kJ kg}^{-1} \text{ }^\circ\text{C}^{-1}$
Aggregate	C_{agg}	0.850
Water (10–100°C)	$C_{\text{H}_2\text{O}}$	4.191
Steam	C_{vap}	1.85
Bitumen at $T^\circ\text{C}$	$C_{\text{bit}}(T)$	$1.779 + 1.967 \times 10^{-3}T$ (Pfeiffer 1950)
Paraffin wax	C_w	2.9
Slaked lime ($\text{Ca}(\text{OH})_2$)	C_{lime}	1.20

It follows from the data above that the heat required to raise a kilogram of bitumen from temperature T_1 to temperature T_2 is given by

$$Q_{\text{bit}}(T_1, T_2) = \int_{T_1}^{T_2} C_{\text{bit}}(T) dT = 1.779 (T_2 - T_1) + 9.835 \times 10^{-4} (T_2 - T_1)^2 \text{ kJ/kg}$$

Equation 3.1

In addition to the above data we require for damp aggregate heated above 100°C the latent heat of vaporisation of water:

$$L_{\text{vap}} = 2270 \text{ kJ kg}^{-1} \quad \text{Equation 3.2}$$

In cases where paraffin wax is present and heated above its fusion range, we need to account for the heat of fusion:

$$L_{\text{fus}} = 220 \text{ kJ kg}^{-1} \quad \text{Equation 3.3}$$

3.2.1 Standard hot mix

Kristjansdottir et al (2007) and Olard, H eritier and Beduneau (2008) took as their standard aggregate mix 65% of coarse aggregate (defined as retained on a 2mm sieve) with 1% water content and fine aggregate with 4% water. The higher water content of the fine aggregate was necessary to achieve bitumen foaming for the LEA method, but in any case the higher surface to volume ratio of fine material will encourage greater absorption of water. For the purposes of comparison these water contents will be assumed for all mixes to be discussed.

Ambient temperature is taken as 10°C and the mixing temperature as 160°C.

Initially, 1000kg of coarse dry aggregate accompanies 1000/99kg of water (ie supplied moist aggregate has 1% water by weight of water plus aggregate).

1000kg of fine dry aggregate accompanies 1000/24kg of water (moist fine aggregate initially has 4% water by weight of water plus aggregate).

Thus, a 1000kg mix of 650kg coarse and 350kg fine aggregate contains $(0.65 \times 1000/99 + 0.35 \times 1000/24) = 21.150\text{kg}$ water.

Heating the 1000kg of aggregate from 10°C to 160°C requires:

$$1000 \times C_{\text{agg}} \times 150 = 127,500\text{kJ} = 127.5\text{MJ}.$$

Heating the 21.150kg of water from 10°C to 160°C requires:

$$21.150 \times [C_{\text{H}_2\text{O}} \times 90 + L_{\text{vap}} + C_{\text{vap}} \times 60] = 21.150 \times 2758.19 = 58,336 \text{ kJ} = 58.336\text{MJ}.$$

Note that the vaporisation of the water at 100°C requires $100 \times 2270 / 2758.19 = 82.3\%$ of the total energy involved in heating the water. Thus, if a methodology of asphalt manufacture can be devised that means the water need not be heated above 100°C there is potential for significant energy saving.

The total heat required for the 1000kg of aggregate plus the water is thus $127.500 + 58.336 = 185.836\text{MJ}$.

If we standardise on a mix containing 5.6% by weight of bitumen, in a tonne (1000kg) of mix we have 944kg of aggregate and 56kg of bitumen. If we take the bitumen as having been heated from 10°C to 170°C, according to equation 3.1 the heat required to raise the bitumen to 170°C is $56 \times Q_{\text{bit}}(10, 170) = 56 \times 309.82 = 17,350\text{kJ} = 17.350\text{MJ}$.

The heat input for one tonne of hot mix is therefore $0.944 \times 185.836 + 17.350 \approx 192.8\text{MJ}$.

The bitumen is heated by electricity. The remainder of the mix (aggregate plus water) will normally be heated via the plant burner by natural gas, heavy fuel oil or diesel.

Patrick and Arampamoothy's (2009) figure of 478MJ/tonne of mix (table 3.1) is approximately 2.5 times this calculated value. Other recently published figures, based on electric power used and the amount of fuel burned, are 466MJ/t (Tighe and Davidson 2008), 287MJ/t (Marchand et al 2008) and 277MJ/t (Dorchies 2008).

Marchand et al (2008) provide the following breakdown for energy consumption in an asphalt plant in Europe:

Table 3.3 Energy consumption for hot mix manufacture according to Marchand et al (2008)

Item	Energy consumption MJ/tonne of mix	Percent of total energy
Aggregates	128	19
Bitumen	229	34
Heavy fuel oil	245	36
Diesel	34	5
Electricity	42	6
Total	678	100

The energy supplied by heavy fuel oil (245MJ/tonne of mix) represents the energy needed to heat the aggregate, and is approximately 36% of the total energy involved in asphalt manufacture. A portion of the electricity consumption (42MJ) would be needed to heat the bitumen, and the rest would be used in running the asphalt plant. Assuming diesel use represents the transport of materials, the total energy required to manufacture a tonne of asphalt is $(245+42) = 287\text{MJ}$. The energy involved in bitumen production (and possibly transport) of 229MJ/t is only 33% of the 70MJ/t for bitumen production cited by Patrick and Arampamoothy (2009) (see table 3.1).

Marchand's figures indicate that electrical energy (42MJ/tonne) constitutes 13.1% of the total energy $(245+34+42=321\text{MJ})$ used in the actual asphalt-making process.

A similar analysis for a Canadian hot mix is given by Dorchies (2008) (table 3.4):

Table 3.4 Energy analysis of typical Canadian hot mix according to Dorchies (2008)

Item	Energy consumption MJ/tonne of mix	Percent of total energy
Aggregates	38	6
Bitumen	244	39
Manufacturing	277	44
Transport	54	9
Laying	11	2
Totals	624	100

The energy expended in asphalt manufacturing (277MJ/tonne) is similar to Marchand's 287MJ/tonne figure. Transport energy expenditure of 54MJ/tonne is exactly the same as would be calculated from table 3.1 for a 20km return trip. If we consider only Dorchies' energy costs for manufacturing, transport and laying, a total of $277+54+11=342$ MJ/tonne, and take Marchand's figure of 42MJ/tonne for the contribution of electricity to this figure, electricity represents $100 \times 42/342 = 12.3\%$ of the energy expenditure.

However, from the contractor's point of view, looking at their total energy expenditure to produce the asphalt, we need to add in the energy cost of aggregate production; this will be largely in terms of electricity. From table 3.1 we adopt the value of 80MJ/tonne of aggregate; for the 944kg of aggregate in one tonne of a hot mix with 5.6% bitumen content, we have energy expenditure from aggregate production of $(944/1000) \times 80 \approx 76$ MJ/tonne asphalt. To get the total electricity input per tonne of asphalt we add this to the 42MJ/tonne cited by Marchand (table 3.3), obtaining a value of 118MJ/tonne. Adding the aggregate energy input to the 342MJ/tonne deduced from Dorchies' figures for manufacturing, transport and laying, the total energy input becomes $342+76 = 418$ MJ/tonne, of which the electricity input makes $100 \times (118/418) = 28\%$. The actual asphalt manufacturing energy (non-electrical) is thus $100 \times (277/418) = 66\%$ of total energy expenditure for the contractor.

A comparison of tables 3.3 and 3.4 suggests that different decisions have been made on the details of the items to include in evaluating energy consumption for hot mix manufacture. For example, it is not clear if Dorchies has included the electrical energy expended in operating the plant in his estimate of the total energy used in manufacturing. Without full details a comparison of different published results can only be indicative at the best.

Going by Dorchies' figures, the non-electrical energy expended in manufacturing the asphalt (277MJ/t) is around 44% of the total energy expenditure (including that of bitumen manufacture) (624MJ/tonne) in producing laid paving. This places an upper limit on the proportion of energy that can be saved by adopting a warm asphalt manufacturing process, and consequently on the potential for reducing emissions.

3.2.2 Comparison of calculated and reported energy inputs

The required energy inputs for the different production processes described in chapter 2 are calculated in appendix A following the methodology of section 3.2.1. These are presented in table 3.6, along with energy inputs and savings claimed in the literature.

Heating inputs for asphalt plants are variously reported, depending on the particular plant, in terms of volumes of natural gas and litres of fuel consumed in the heating process, as well as different energy

units. To enable comparisons, inputs have been standardised to megajoules (MJ) of energy per tonne of mix produced (MJ/t), using the following approximate equivalences:

Table 3.5 Approximate energy content of fuels

Energy source	Energy equivalent
Natural gas	37MJ/m ³
Diesel	38.6MJ/l

Table 3.6 Comparison of heating energy for different mix processes

Production method		Calculated energy to heat one tonne of aggregate		Calculated energy to heat one tonne of mix		Reported heating (MJ/t) for mix	Reported % heating savings for mix
		MJ/tonne	Energy % reduction	MJ/tonne	Energy % reduction		
Standard hot mix		185.8	0	192.8	0	292 ¹ , 439 ⁵ , 330 ⁷	
KGO-III		159.2	14.3	150.5	21.9		
WAM foam process		155.6	16.3	163.6	15.1		30□40 ² , 32 ³
Viscosity reducing organic additives		168.1	9.5	174.5	9.5	244 ¹	16 ¹ , 20 ²
Low dosage anhydrous additives		150.3	19.1	141.9	26.4		25 ⁶ 20□50 ⁸
Zeolite additives		159.2	14.3	167.6	13.1	256 ¹	12 ¹ , 30 ² , 23 ⁴
Hot emulsion based		163.6	11.9	199.8	-3.6	382 ¹ , 201 ⁵	-21 ¹ , 50-75 ² , 54 ⁵
Foam mix	Typical	163.6	11.9	171.7	10.9		
	Double Barrel Green	150.3	19.1	159.2	17.4	250 ⁷	24 ⁷
LEA processes A & B		84.0	54.8	96.6	49.9		
LEA process C		108.5	41.6	119.7	43.1		64

¹Ursich 2008, ²Kristjansdottir et al 2007, ³Larsen et al 2004, ⁴Marchand et al 2008, ⁵Tighe and Davidson 2008, ⁶Grampre et al 2008, ⁷Middleton and Forfyflow 2009, ⁸CECA 2007

Apart from the hot emulsion-based asphalt the calculated heating energy expenditures are less than reported results. The differences may reflect, at least partly, unavoidable inefficiencies and losses. However, there may be considerable opportunity for significant energy savings by maximising efficiency through good insulation, burner adjustment and covering aggregate to minimise moisture content.

Measured data is not available for all processes, and so for comparative purposes it will be necessary to use the calculated figures. Many processes have the potential to give heating energy savings of the order of 20%; the half-warm processes can give around double this figure. The situation with the hot emulsion based process is not clear, but it is likely that the energy savings of asphalt manufacture at reduced temperatures are negated by the energy expended in manufacturing the emulsion.

4 Emissions

The lower production temperatures for warm and half-warm mixes mean that less fuel is needed to heat the aggregate and lower emissions will result. The actual reductions vary, based on a number of factors, and need to be considered on a case-by-case basis.

D'Angelo et al (2008) report that plant stack emissions are significantly reduced; CO₂ reductions are of the order of 20% to 40%; SO₂ 20% to 35%. The reduction of volatile organic compounds can be up to 50% and, for carbon monoxide (CO) 10% to 30%. For nitrous oxides (NO_x) the reduction can be as much as 60% to 70%. A general rule is that emissions of greenhouse gases like NO₂ and CO₂ are reduced in proportion to the energy saving (EAPA 2009). Data on the CO₂ footprint of the various additives is not readily available; it is possible that in many cases this footprint may outweigh the savings gained from energy and emissions reductions (EAPA 2009).

In absolute terms, Fulton Hogan, Christchurch (Pidwerbesky, pers comm 28 August 2009) report that the asphalt production process (165°C) produces 0.0248 tonnes of CO₂ per tonne of asphalt. Their Coolpave process produces 0.0144 tonnes of CO₂ per tonne of mix, ie a 41.9% reduction in CO₂ emissions (or 10.4kg/tonne of mix reduction). The production figures include bulk fuel (diesel, petrol), diesel as fuel for plant, reticulated gas for heating, waste oil as fuel for plant and electricity.

If 'embedded' carbon is included (to the above we add electricity transmission losses, gas transmission losses, embedded carbon in aggregates, melter slag and bitumen) the figures become 0.0378 tonnes CO₂/tonne hot mix and 0.0274 tonnes CO₂/tonne Coolpave, a 27.6% reduction.

Agrilink New Zealand (2008) provides a set of figures for carbon dioxide equivalent (CO₂ eq) emissions for different types of fuel energy. Using these figures and energy requirements as indicated (table 4.1) we can calculate the equivalent CO₂ emissions for a tonne of asphalt.

Table 4.1 Calculated equivalent CO₂ emissions for asphalt manufacture

Item	Energy consumption MJ/tonne of mix (5.6% bitumen)	Assumed fuel type	⁴ gCO ₂ eq/MJ	kg CO ₂ eq emitted
Aggregates	¹ 75.52	Electricity	30.4	2.3
Manufacturing	² 42	Electricity	30.4	1.3
	³ 277	HFO	71.21	19.7
Transport	³ 54	Diesel	68.8	3.7
Laying	³ 11	Diesel	68.8	0.8
Total kg CO ₂ eq				27.8

¹80 MJ/tonne of aggregate (table 3.1); 0.944 tonnes aggregate in 1 tonne of mix, ²Marchand et al (2008) - see table 3.3, ³Dorchies (2008) - see table 3.4, ⁴Agrilink New Zealand (2008)

This is in fair agreement with Fulton Hogan's figure (23.8kg CO₂ eq/tonne asphalt). The only CO₂ emission that can be affected by converting to warm mix manufacture is the 19.7kg CO₂ fuel oil contribution (71% of the total output).

Use of natural gas (53.36gCO₂ eq/MJ) instead of fuel oil (a possibility for some North Island asphalt plants) reduces the calculated CO₂ fuel emissions from 19.7 to 14.8kg per tonne of asphalt, and total emissions to 22.9kg CO₂/tonne of asphalt, a reduction of 17.6% of the total CO₂ emissions.

The 24% savings reported for the Double Barrel Green process (table 3.6) amounts to $0.24 \times 19.7 = 4.7\text{kg/tonne}$ of mix; applied across the approximately million tonnes of asphalt manufactured per year this amounts to a reduction of 4700 tonnes of CO_2 (equivalent) that could be attained. The 10.4kg/tonne of mix reduction of CO_2 emission reported by Fulton Hogan would, if applied to all New Zealand asphalt production, give a total reduction of 10,400 tonnes of CO_2 . Based on energy expenditure calculations (table 3.6), anhydrous chemical additive technologies at their present state of development should give CO_2 emissions between the above two values.

Total equivalent CO_2 emissions for New Zealand in 2007 (the latest reported results) were 75.6 million tonnes (Ministry for the Environment 2009), with 43.2% of this due to energy production and 48.2% to agriculture. Of this, road vehicles contributed an estimated 13.3 million tonnes CO_2 equivalent.

In terms of emissions from the asphalt production industry, warm and half-warm technologies have the potential to make a significant reduction to CO_2 emissions. However, given the total CO_2 equivalent emissions for New Zealand, this needs to be accompanied by a wide variety of other emission control strategies.

5 Comparative costs of different processes

Cost reductions for warm mixes may arise because:

- less fuel is needed to dry and warm the aggregate to the reduced production temperature
- lower production temperatures usually result in less wear of the asphalt plant (Rühl 2008)
- for at least one technology (Viman et al 2008) a lower bitumen content is required.

Cost increases may arise from:

- the investment and depreciation of any needed plant modification
- the costs of any special additives required
- any technology licensing costs.

Table 5.1 lists available cost increases in US dollars, where these have been found in the literature.

Table 5.1 Published cost increases (US dollars) for various warm and half-warm mix processes

Production method		Equipment modification or installation costs	Royalties	Material cost	Additive dosage (recommended)	Approximate increased cost /tonne of mix
KGO-III		Modification needed – cost unavailable ¹			None	Unpublished
WAM foam process		\$60,000 □ \$85,000	\$15,000 first year/\$5000 per plant/\$0.35 per tonne	\$75/tonne premium on soft bitumen	Surfactant and anti-stripping agent may be needed	\$0.27-\$0.35 /tonne royalty
Viscosity reducing organic additives		\$5000 □ \$40,000 (Sasobit)	None	\$1.75/kg	1.5% □ 3.0% by wt of binder	\$2.00 □ \$3.00 /tonne
Low dosage anhydrous additives					0.2 – 0.5% by wt of binder	
Zeolite additives		\$5,000-\$40,000	None	\$1.35/kg	0.3% by wt of mix	\$3.60 □ \$4.00 /tonne
Hot emulsion based		\$1,000-\$5000	None	\$35 □ \$50 premium on binder	30% water/70% bitumen	\$3.50 □ \$4.00 /tonne
Foam mix	Typical				Anti-stripping agent may be added	
	Double Barrel Green	\$100,000 □ \$120,000 ²	None	None	None	
LEA processes: A & B		\$75,000-\$100,000	Not applicable	Coating additive 0.5% of binder weight	0.5% by wt bitumen of coating additive	\$0.50 □ \$1.00/tonne
LEA process C						

Unless otherwise indicated, prices follow Kristjansdottir (2007), ¹Viman et al (2008), ²Requires Astec Double Barrel drum (Middleton and Forfylov 2009)

6 Asphalt and binder physical properties

6.1 Asphalts

Published results from laboratory testing of mixes produced by different methods generally come to the conclusion that the performance of warm mixes at normal road temperatures is similar to or slightly better than equivalent standard asphalt mixes (Hurley and Prowell 2006a, b; Hurley and Prowell 2005a, b; Olard, le Noan et al 2008; EAPA 2009; Grasper et al 2008; Ghandi et al 2010). Asphalts generally have comparable resistances to moisture (despite the frequent use of water for foaming) and resilient moduli.

Several reasons have been proposed for this good performance. Improved workability of the warm and half-warm products can result in a higher compacted density being achieved, resulting in reduced long-term hardening and less opportunity for water penetration, and reduced susceptibility to rutting. Lower production temperatures should also decrease the oxidative hardening of the bitumen during the production stage and improved resistance to thermal and fatigue cracking may result.

Comparative results of different manufacturing processes will to some extent depend on the aggregate type and grading; New Zealand mixes are generally produced with fully crushed aggregates and sensitivity to variation of binder properties may not be great.

6.2 Binders

Further insight into the effect of the different warm mix processes could be obtained by studying the rheological properties of the binders containing the different warm asphalt additives but this has not been done to any great extent.

Some hardening of the binder is expected during production, but there does not appear to have been any work done which takes this into account. A rolling thin film oven treatment carried out at around 130°C (instead of the standard 163°C) would produce test binders that are closer in physical and chemical properties to those from the asphalt plants.

Apart from reduced hardening due to the lower processing temperatures, there will be changes where additives are used. Some information has been published, as follows.

6.2.1 Organic waxes □ Sasobit

Naidoo (2006), in his presentation at the World Asphalt Conference in Florida, presented a set of graphs for a 50/70 penetration grade bitumen containing various quantities of Sasol wax, from which the rheological properties listed in table 6.1 can be read.

The viscosities at 135°C decrease with increasing Sasol wax content, as required to allow asphalt production at reduced temperatures. At 60°C the situation is reversed as a result of crystallisation of the Sasol wax; this reversal is also reflected in increased softening points and reduced 25°C penetrations. The sensitivity to temperature of the binder, as measured by the increased (softening point/25°C penetration) penetration index, is reduced by the addition of wax, especially at greater than 1.5% dosages. Thus, although the effect of the wax is to harden the binder at ambient temperatures (increased 25°C penetration), if the observed trends continue to lower temperatures the rheological properties of the binders may converge.

Table 6.1 Effect of Sasol® wax on rheological properties of a 50/70 bitumen (Naidoo 2006)

Sasol wax content, %	0	1.5	3.0	4.0
Viscosity at 135°C, Pa.s	0.307	0.275	0.250	0.229
Viscosity at 60°C, Pa.s	125	360	848	1020
Softening point (Ring and Ball), °C	46	49	68.5 ¹	80
Penetration at 25°C, dmm	84	61	53.6 ¹	51
Penetration index ²	-0.992	-0.987	2.770	4.736

¹Interpolated values, ²Calculated from the softening point and 25°C penetration values

Nevertheless, there is some concern in the USA that at low winter temperatures Sasol doped bitumens may be subject to cracking. For the American performance graded system it has been suggested that with typical wax dosage a change of one grade at both upper and lower specification temperatures occurs (eg with 2.5% Sasobit added a PG 58□28 bitumen became a PG 64□22 binder (Hurley and Prowell 2006a)). Thus the resultant binder is expected to be suspect in lower winter environmental temperatures. The less extreme winter temperatures generally experienced in New Zealand make this less of a concern here.

6.2.2 Zeolites □ Aspha-Min

Szabolcs et al (2009) compared five bitumens with Aspha-Min (0.3%) and Sasobit (1.5%) added. At 60°C viscosities of all dosed products were increased, but the effect was notably greater for the Sasobit. The viscosity increase for the Aspha-Min products was attributed to the Aspha-Min acting as a filler.

6.2.3 Anhydrous chemical additives □ Cecabase RT

Grampre et al (2008) investigated the effect of the Cecabase RT additive. Addition of the additive resulted in a slight reduction (approximately 5%) of the binder viscosity at 120°C which they considered insufficient to account for the 50°C reduction that was obtained in the mixing process. They concluded that the improved compaction is associated with the interaction at the aggregate binder interface. This being so, effectiveness of the method may vary from aggregate to aggregate and bitumen to bitumen.

7 Application to New Zealand practice

7.1 Current practice in New Zealand

Fulton Hogan are promoting the use of their half-warm product Coolpave® and have reported laying mixes in Auckland, Christchurch and Dunedin and at Christchurch airport (Pidwerbesky and McDonald 2008; Hayward and Pidwerbesky 2009).

Downer EDI Works currently have the Astec system operating in Auckland (pers comm, J. Starr, Downer EDI Works, 28 January 2010).

7.2 Research and testing

Button et al (2007) suggest that the following matters need research:

- Because of the lower mixing temperature, does WMA yield less binder absorption into the aggregates? If so, how will lower absorption affect mixture design (optimum asphalt content) and long-term performance (eg moisture susceptibility)?
- Some WMA products have significantly lowered air voids during standard gyratory compaction as compared to similar HMA, which indicates reduced optimum asphalt content. Will the reduced asphalt content lead to problems related to durability (eg cracking, oxidative aging and/or moisture susceptibility)?
- For testing HMA in the laboratory, there are essentially no cure time requirements for specimens. Are these procedures acceptable for WMA specimens, or is some cure time needed to expel the moisture for certain WMA products to yield realistic predictions of performance?
- Less heat energy for WMA processes is likely to leave more moisture in the aggregates and, thus, in the compacted mat. How will this potential moisture affect short-term and long-term pavement performance?
- With less oxidative aging in the plant, should one start with a harder asphalt binder than typically used for HMA? If not, will the less aged, softer binder combined with the potential moisture in some WMA mixtures lead to premature permanent deformation?
- Will some cure time be required for WMA products containing moisture before traffic can be allowed on it without concern about permanent deformation?

The answer to each of these matters will depend on the mix technology used. To date no problems of importance have been reported, but it is recommended that a watching brief should be kept on overseas research. Long-term performance for different processes will not become evident until they have been in use for a sufficient time, possibly for another 10 to 15 years for some recently developed technologies.

The absence of extensive studies on laboratory sample preparation and quality control means that modification of the specification for asphaltic concrete, TNZ M/10 (Transit NZ 2005a), to accommodate warm mix would not be straightforward. One option would be to prepare equivalent hot mix samples, but this procedure might result in selection of binder content levels higher than ideal for at least some warm mix processes (Viman et al 2008). For instances where the modified binder is hardened at ambient and lower temperatures (eg Sasobit®), consideration may need to be given to the use of 130/150 bitumen on occasion. The alternative would be to accelerate the development of a performance-based specification for asphalt: TNZ P/23 (Transit NZ 2005b). As this type of specification is primarily based on the ultimate

properties of the finished pavement, it could be developed so that it would be applicable for all mix processes.

7.3 Economics

In the survey conducted by Kristjansdottir et al (2007), several respondents indicated that WMA would only be an option if it cost the same as or less than HMA, unless:

- environmental regulations were made stricter, or
- it provided some quality or construction benefit (then a moderate increase in cost would be acceptable).

At present neither of these possibilities has occurred in New Zealand.

The increasing cost of energy over time may eventually make warm mix asphalts a more attractive option; incentives for reduced emissions would help here. In the short run greater gains may be made in maximising efficiency of hot mix plants through such measures as aggregate stockpile moisture management, burner adjustment for greater efficiency, improvement of plant insulation and use of recycled asphalt.

It is possible that the reduced binder hardening and increased compaction obtained with some methodologies may give longer pavement lifetimes. In addition, the lower mixing temperatures may make it possible to extend the range of acceptable bitumens to ones which have a greater volatility at elevated temperatures. If these possibilities turn out to be clearly the case in the long run, the client rather than the contractor will be the beneficiary, and it will be necessary for clients to specify use of a warm or half-warm asphalt manufacturing process.

7.4 Adoption in New Zealand

At this stage in the development of the technologies none appear to be especially suited to New Zealand conditions. Environmental advantages due to reduced fuel consumption will need to be balanced against costs of additives and modifying plant and the varying maturity of the different technologies. Consequently no recommendation covering all cases can be made at present.

Different methodologies will appeal to different asphalt producers, depending on a number of factors such as potential market size and available capital for plant investment. Some asphalt producers may not be able to financially justify the refurbishment of existing asphalt plants needed for some of the warm mix technologies. In this case products that involve the use of small quantities of additive with minimum plant change would appeal. The use of organic additives (eg Sasobit, Ecoflex,) or anhydrous chemical additives (Cecabase RT, Rediset WMX) may be indicated. The latter may present a higher initial risk because they probably work through affecting the interaction at the aggregate binder interface, and their effectiveness may consequently vary with aggregate chemistry, aggregate grading and bitumen source. Laboratory testing may be needed before a decision to go down that path. Ultimately the anhydrous chemical additives may have a significant advantage over other additive-based technologies as experience with their use develops, because of the relatively low temperatures at which they can be used (table 2.1) and the estimated greater energy savings (table 3.6).

Other asphalt manufacturers will probably, as they renew asphalt plant, be inclined to install equipment that can produce foam mixes. In the long term they may be attracted to half-warm technologies despite the setting up costs, in view of the potentially larger energy savings. This advantage should increase as

energy costs increase and if greater incentives to reduce emissions are adopted by government and/or local authorities. At present the balance of costs means that warm and half-warm mixes cost the producer more than hot mixes.

Overall, the LEA processes and, to a lesser extent, use of anhydrous chemical additives look to have the greatest long-term potential because of the energy savings associated with reduced temperatures. A watching brief on the use and development of these two technologies in particular is recommended. Proposals to trial and apply these technologies to asphalt manufacture should be encouraged.

Mix design and quality control of mix production require developing laboratory procedures which closely match the large-scale production processes. If particular processes look to become widely established in New Zealand, research to develop such procedures and evaluate their effectiveness should be carried out. A watching brief on the development of quality control procedures is recommended.

8 Summary of study results

Warm asphalts are asphalts produced at significantly lower temperatures than the approximately 160°C used at a hot mix plant. Depending on the technology used, laying and compaction may also be possible at significantly reduced temperatures.

The technologies are based on at least one of the following five principles:

- 1 Modification of the asphalt mixing process (without changing the mix components). Significant plant modifications are necessary. Paving is completed at similar temperatures as for standard mixes for compaction.
- 2 Addition of substances which decrease the viscosity of the bitumen in the high temperature region. Various waxes are used; these enable mixing at reduced temperatures. Below the wax's softening range the binder is harder than the original bitumen, and paving cannot be carried out at reduced temperatures; alternatively it may be appropriate to use a softer grade of bitumen. Minor plant adjustment to allow addition of the wax in controlled amounts may be necessary.
- 3 Modification of the bitumen-aggregate interaction. Proprietary chemical additives have been developed which improve the mix workability and aggregate coating without changing the bitumen viscosity significantly. Mixing and paving can both be carried out at significantly reduced temperatures. The effectiveness of the additives may vary from bitumen to bitumen and aggregate to aggregate. Apart from apparatus to inject the additive into the bitumen, no plant modification is needed.
- 4 Introduction of water to foam the bitumen. This may be achieved by
 - a) foaming of bitumen in the asphalt plant before application to heated aggregate. Modified or specialised plant is required
 - b) use of zeolite additives which slowly release water above 100°C
 - c) addition of a warm bitumen emulsion (ca 90°C) to heated aggregate. Energy savings may be minimal or even negative for this process, owing to the need to manufacture the emulsion. However, paving at significantly reduced temperature is possible
 - d) addition of water to a finer part of the aggregate to promote foaming when the bitumen is added. This process allows both mixing and paving to be carried out at significantly reduced temperatures, and is classified as 'half warm' rather than simply 'warm'. Considerable plant modification may be necessary, and a significant royalty payment is required when setting up.
- 5 Use of low viscosity vegetable binder. No published material on the effectiveness or behaviour of these products was available at the time this report was prepared.

Details are supplied in this report for examples of the first four of these technologies, and typical values calculated for the energy needed to produce a tonne of mix.

Published results for fuel and electricity consumption of the hot mix process indicate that the energy expended in heating the aggregate and bitumen (approximately 277MJ/tonne of mix) is around 44% of the total energy involved in production, transport, laying and rolling of asphalt. This places an upper limit on the proportion of energy expended that can be saved by adopting a warm asphalt manufacturing process.

Apart from the warm emulsion-based asphalt the calculated heating energy expenditures are less than reported results. The differences may reflect, at least partly, unavoidable inefficiencies and losses.

However, there may be considerable opportunity for significant energy savings by maximising efficiency through good insulation, burner adjustment and covering aggregate to minimise moisture content.

Measured data are not available for all processes, and so for comparative purposes it is necessary to use calculated figures. These indicate that many processes have the potential to give heating energy savings of the order of 20%; the anhydrous chemical additives may give somewhat better savings than this, while the half warm processes can give around double this figure. The situation with the hot emulsion based process is not clear, but it is likely that the energy savings of manufacture at reduced temperatures are negated by the energy expended in manufacturing the emulsion.

The lower manufacturing temperatures will result in reduced emissions of carbon dioxide and other organic gases. A typical warm asphalt process would, if adopted throughout New Zealand, result in an annual reduction of CO₂ equivalent emissions of approximately 4700 tonnes. The LEA half warm process would roughly double this, but adoption of this process may not be financially justifiable for some asphalt producers, because of the cost of the necessary plant refurbishment.

Currently the balance of savings and costs of warm mix technology results in warm mixes being more expensive than the equivalent standard hot mixes.

As a rule asphalts produced by warm mix processes have comparable resistances to moisture (despite the frequent use of water for foaming) and resilient moduli. Improved workability of the warm and half-warm products can result in a higher compacted density being achieved, resulting in reduced long-term hardening, less opportunity for water penetration, and reduced susceptibility to rutting.

Asphalt lifetimes may be affected by the hardness of the binder at ambient temperatures. Apart from reduced hardening due to the lower processing temperatures, there will be increases in some cases where additives are used, in particular for organic waxes and, to a lesser extent, zeolites.

The principal advantages of warm asphalt technology are claimed to be:

- reduced heating fuel requirements
- reduced carbon dioxide, other greenhouse gases and volatile organic compounds emissions
- increased time available for transport, laying and compaction
- ability to pave satisfactorily at lower ambient temperatures. This is the case only for certain technologies
- increased safety for operators
- longer surface life due to decreased binder oxidation and improved compaction.

Possible disadvantages may include

- an increased susceptibility to stripping proposed due to residual water resulting from foaming and/or lower mixing/compaction temperatures (Button et al 2007, p37). No conclusive evidence has been reported for this to date
- higher susceptibility to rutting due to the binder's not being so hardened by the manufacturing process (controllable by using a harder binder)
- greater expense from additives, plant modification and purchase of patent rights.

In New Zealand, Fulton Hogan Ltd and Downer EDi Works Ltd possess plant capable of producing warm or half-warm asphalt mixtures.

Manufacturing warm mixes currently costs more than for hot mixes, although future anticipated increases in energy costs will probably change this situation.

At this stage in the development of the technologies none appear to be especially suited to New Zealand conditions. Environmental advantages due to reduced fuel consumption will need to be balanced against costs of additives and modifying plant and the varying maturity of the different technologies.

Consequently no recommendation covering all cases can be made at present.

Procedures for laboratory design of warm and half-warm mixes appear to be still in the developmental stage. Watching briefs are recommended in particular for:

- use and innovation with the LEA and anhydrous chemical additives processes
- the development of quality control procedures and specifications
- information on the long-term pavement performances obtained with the various technologies.

Present indications are that warm and half-warm mixes can be produced that have similar performance to hot mixes, and provision should be made to be ready to adopt these technologies for the state highway network through suitable quality control procedures. At present asphalt quality control is usually carried out in accordance with TNZ M/10: 'Specification for asphaltic concrete' (Transit NZ 2005a). The mix design method specified in this standard is inappropriate for warm asphalts; to continue with the M/10 approach a different method for each warm mix technology would be needed. It is therefore recommended that an alternative development of a performance-based specification for asphalt, currently TNZ P/23 (Transit NZ 2005b), be accelerated. This type of specification is primarily based on the ultimate properties of the finished pavement, so that it could be developed to be suitable for all mix processes.

In terms of emissions from the asphalt production industry, warm and half-warm technologies have the potential to make a significant reduction to CO₂ emissions. However, given the total CO₂ equivalent emissions for New Zealand, this needs to be accompanied by a wide variety of other emission control strategies.

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Appendix A: Calculations of production process energy input

Introduction

This appendix applies the methodology used in section 3.2.1 for calculating the energy input to a standard hot mix to a number of warm and half-warm mix methodologies. The thermal property values listed in tables 3.1 and 3.1 are used as appropriate.

Common to all calculations is the heat required to bring aggregate containing various quantities of absorbed water to the appropriate mixing temperature. For a kilogram of aggregate containing w% water (1000w/(100-w)kg of water) from 10°C to T°C the amount of heat required, H_{agg}, is:

$$H_{agg} = 1000 \times C_{agg} \times (T - 10) + [1000w / (100 - w)] \times [(T \leq 100) \times C_{H2O} \times (T - 10) + (T > 100) \times (L_{vap} + C_{vap} \times (T - 100))] \quad \text{Equation A.1}$$

Figure A.1 Heat input in MJ required to heat from 10°C one tonne of aggregate with standardised water content (65% with 1% water and 35% with 4% water)

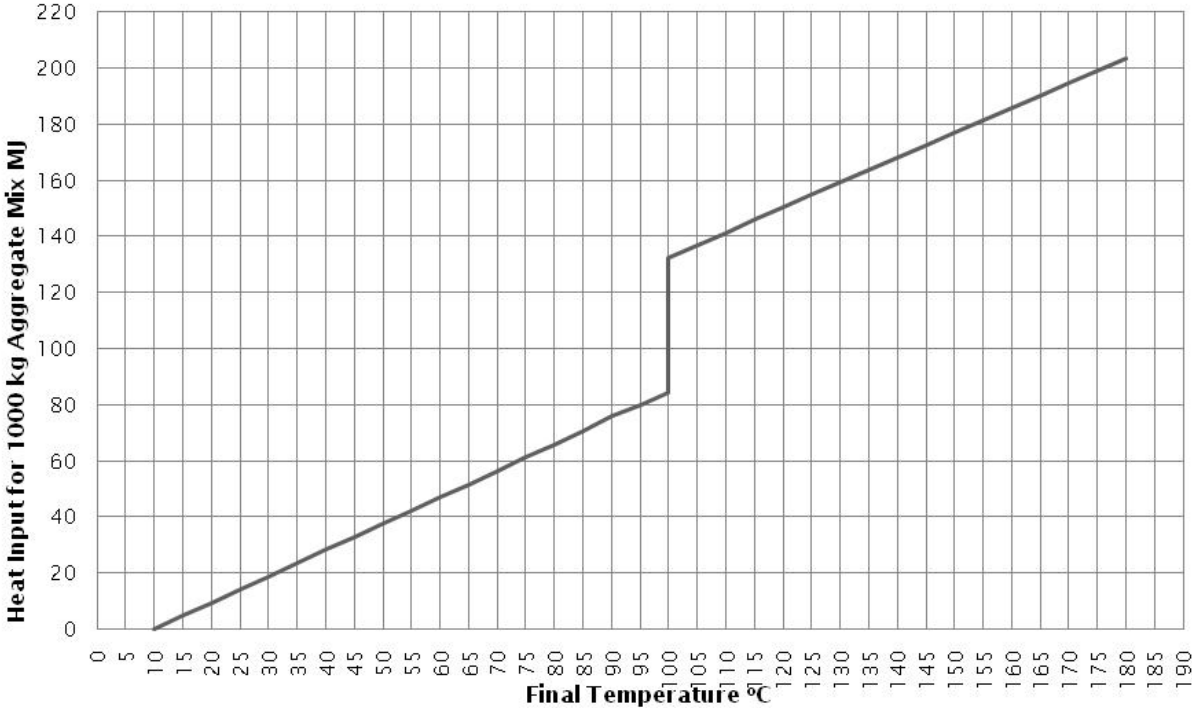


Table A.1 Heat input in MJ required to heat one tonne of aggregate with various water contents from 10°C

Final temperature °C	Heat for 1kg water kJ/kg	1000kg dry aggregate	1000 kg aggregate + 1%H ₂ O	1000 kg aggregate + 4%H ₂ O	1000 kg aggregate 65% with 1% H ₂ O 35% with 4% H ₂ O
15	20.955	4.3	4.5	5.1	4.7
20	41.91	8.5	8.9	10.2	9.4
25	62.865	12.8	13.4	15.4	14.1
30	83.82	17.0	17.8	20.5	18.8
35	104.775	21.3	22.3	25.6	23.5
40	125.73	25.5	26.8	30.7	28.2
45	146.685	29.8	31.2	35.9	32.9
50	167.64	34.0	35.7	41.0	37.5
55	188.595	38.3	40.2	46.1	42.2
60	209.55	42.5	44.6	51.2	46.9
65	230.505	46.8	49.1	56.4	51.6
70	251.46	51.0	53.5	61.5	56.3
75	272.415	55.3	58.0	66.6	61.0
80	293.37	59.5	62.5	71.7	65.7
85	314.325	63.8	66.9	76.8	70.4
90	377.19	68.0	71.8	83.7	76.0
95	356.235	72.3	75.8	87.1	79.8
100	377.19	76.5	80.3	92.2	84.5
100	2647.19	76.5	103.2	186.8	132.5
105	2656.44	80.8	107.6	191.4	136.9
110	2665.69	85.0	111.9	196.1	141.4
115	2674.94	89.3	116.3	200.7	145.8
120	2684.19	93.5	120.6	205.3	150.3
125	2693.44	97.8	125.0	210.0	154.7
130	2702.69	102.0	129.3	214.6	159.2
135	2711.94	106.3	133.6	219.2	163.6
140	2721.19	110.5	138.0	223.9	168.1
145	2730.44	114.8	142.3	228.5	172.5
150	2739.69	119.0	146.7	233.2	176.9
155	2748.94	123.3	151.0	237.8	181.4
160	2758.19	127.5	155.4	242.4	185.8
165	2767.44	131.8	159.7	247.1	190.3
170	2776.69	136.0	164.0	251.7	194.7
175	2785.94	140.3	168.4	256.3	199.2
180	2795.19	144.5	172.7	261.0	203.6

Table A.2 Heat to increase bitumen temperature

Final temperature °C	$Q_{bit}(10,T)$ kJ/kg (equation 3.1)	Heat Input for 56kg (MJ)
10	0.00	0.0
15	8.92	0.5
20	17.89	1.0
25	26.91	1.5
30	35.97	2.0
35	45.09	2.5
40	54.26	3.0
45	63.47	3.6
50	72.73	4.1
55	82.05	4.6
60	91.41	5.1
65	100.82	5.6
70	110.28	6.2
75	119.79	6.7
80	129.35	7.2
85	138.96	7.8
90	148.61	8.3
95	158.32	8.9
100	168.08	9.4
100	168.08	9.4
105	177.88	10.0
110	187.74	10.5
115	197.64	11.1
120	207.59	11.6
125	217.59	12.2
130	227.64	12.7
135	237.74	13.3
140	247.89	13.9
145	258.09	14.5
150	268.34	15.0
155	278.63	15.6
160	288.98	16.2
165	299.37	16.8
170	309.82	17.3
175	320.31	17.9
180	330.85	18.5

Results for a selection of water contents are presented in table A.1. The results for a standardised mix (650kg aggregate with 1% water and 350kg aggregate with 4% water content) are graphed in figure A.1.

The heat input to bring a kilogram of bitumen from 10°C to target temperature, and also for 56kg (the amount in a tonne of mix with 5.6% bitumen content), calculated from equation 3.1, is shown in table A.2.

KGO-III addition sequence process

According to publicity material for this method (Ohlson 2009) the production temperature for the process can be reduced to 130 to 140°C, ie by about 30°C.

To bring 1000kg of aggregate plus the adsorbed water to 130°C requires 159.2MJ of energy. The total heat input calculated for a tonne of aggregate heated to 160°C was 185.8MJ (see section 3.2.1) so we are looking at a reduction of 26.6MJ/tonne.

Thus, the percent reduction in heating aggregate to 130°C instead of 160°C is:

- $100 \times 26.6 / 185.8 = 14.3\%$.

For the complete mix, standardised at 5.6% bitumen, we have the heat input for a tonne of mix as:

- $0.944 \times 159.2 + 56 \times Q_{\text{bit}}(10, 130) / 1000 = 150.5\text{MJ}$.

$Q_{\text{bit}}(10, 130)$ is as defined in equation 3.1.

The total heat input calculated for a tonne of standardised hot mix in section 3.2.1 was 192.8MJ, so we have a reduction of 42.3MJ, or 21.9%.

Warm asphalt mix (WAM) foam process

According to Larsen et al (2004) two grades of bitumen are chosen, with the viscosity of the soft component such that at 100°C it can coat the mineral aggregates. The hard component is added as foam, with the ratio of bitumen components chosen to give an appropriate final penetration value for the mixed bitumen. In the great majority of instances cited by Larsen et al (2004) the target was to produce a 70/100 penetration grade product with a soft bitumen with 60°C viscosity of the order of 1.5 Pa.s (Grade V1500 by Norwegian specification) and a 50/70 bitumen. To produce a 70/100 bitumen we need approximately 12% of the softer bitumen and 88% of the harder. The published material indicates that lime is typically added at 5% to promote adhesion.

The aggregate is typically heated to 130°C, so for 1000kg of solid material we have 650kg of coarse dry aggregate, 300kg of fine dry aggregate and 50kg of lime. A 1000kg of this mix contains $(0.65 \times 1000 / 99 + 0.30 \times 1000 / 24) = 19.066\text{kg}$ of water.

To heat this material from 10°C to 130° requires:

- $950 \times C_{\text{agg}} \times 120 + 50 \times C_{\text{lime}} \times 120 + 19.066 \times [C_{\text{H}_2\text{O}} \times 90 + L_{\text{vap}} + C_{\text{vap}} \times 30] = 155,629 \text{ kJ} = 155.629\text{MJ}$, ie 83.7% of the heat required to heat the aggregate for hot mix production.

The hard bitumen is heated to 170°C, as a high temperature facilitates foaming.

The soft bitumen is heated to, typically, 120°C.

Thus, if total bitumen content in 1000kg of mix is 56kg (5.6%) the heat required to raise the bitumen temperatures is $56 \times (0.88 \times Q(10, 170) + 0.12 \times Q(10, 120)) = 56 \times (272.639 + 24.911) = 16,662.8 \text{ kJ} \approx 16.663\text{MJ}$.

Total heat to produce a tonne of WAM asphalt is therefore $0.944 \times 155.629 + 16.663 \approx 163.6 \text{ MJ}$ as against 192.8 MJ for hot mix.

The energy saving is thus $29.2 \text{ MJ/tonne} = 15.1\%$.

Viscosity reducing organic additives

The most commonly cited material used is Sasobit®, which is a product of Sasol Wax. It is a fine, crystalline, long-chain aliphatic hydrocarbon produced from coal gasification using the Fischer-Tropsch (FT) process (Hurley and Prowell 2005a; Damm et al 2002) The Sasobit® has a carbon chain length range of C_{45} to C_{100} . By comparison, microcrystalline bituminous paraffin waxes have carbon chain lengths ranging from C_{25} to C_{50} . The longer carbon chains in the FT wax lead to a higher melting temperature range (in the vicinity of 100°C), while the smaller crystalline wax structure reduces brittleness at low temperatures as compared to bitumen paraffin waxes.

Publicity material suggests adding 3% to 4% Sasobit® to obtain a reduction in production temperature of 10 to 30°C . We will assume a 20°C reduction to 140°C .

Edwards et al (2006) comment that 'Sasobit is completely soluble in bitumen at temperatures above 140°C '. We will therefore assume the bitumen is heated to 150°C , with a total binder content of 5.6% and a 4% Sasobit content which Edwards et al (2006) say is optimal.

Assuming the standardised aggregate (65% with 1% water, 35% with 4% water), the heat required to bring it to 140°C is 168.1 MJ , ie 90.5% of that required to heat the aggregate to 160°C .

The 56kg of binder consists of 4% Sasobit® (2.24kg) and 53.76kg of bitumen. Specific heat and heat of fusion values for Sasobit® wax are not available, and so are assumed to be the same as for ordinary paraffin waxes, ie $2.9 \text{ kJ kg}^{-1} \text{ }^\circ\text{C}^{-1}$ and 220 kJ kg^{-1} respectively). Heating the binder to 150°C requires $53.76 \times 268.34 + 2.24 \times [(2.9 \times 140) + 220] = 14426.0 + 1402.2 = 15828.2 \text{ kJ} \approx 15.8 \text{ MJ}$. The total heat input for a tonne of mix is therefore $0.944 \times 168.1 + 15.8 = 174.5 \text{ MJ}$ as against 192.8 MJ for hot mix.

The energy saving is thus $18.3 \text{ MJ/tonne of mix} = 9.5\%$.

Low dosage anhydrous chemical additives

Mixing can be carried out at 120°C .

Based on tables A.1 and A.2, with the standardised water content:

- Heat required to heat the 1000kg of aggregate to $120^\circ\text{C} = 150.3 \text{ MJ}$, a saving of $185.8 - 150.3 = 35.5 \text{ MJ}$ or 19.1%.
- Heat required to heat 1000kg of asphalt = $0.944 \times 150.3 + 11.6 = 141.9 \text{ MJ}$ as against 192.8 MJ for the standardised mix. The energy saving is then $50.9 \text{ MJ/tonne of mix}$, ie 26.4%.

Zeolite additives

The artificial zeolite Aspha-Min® is added at approximately 0.3% of mass of the mix, ie 3kg per tonne of mix. It contains approximately 21% of water, which is released gradually in the temperature range of 85°C to 180°C . The additional water, comprising approximately 0.06% of mix weight, is negligible compared to water usually present in the aggregate.

A reduction of up to 30°C in typical hot mix production has been claimed, although 20°C seems typical of some reported trials.

In the event of a 30°C reduction, we have aggregate heated to approximately 130°C. The bitumen is unchanged before it is added to the mix, so we will take it as being at a typical temperature of 170°C.

As determined in 9.2 (KGO-III process) the heat required to bring 1000kg of aggregate to 130°C is 159.2 MJ, with an energy saving of 26.6 MJ/tonne aggregate, ie 14.3%.

The bitumen energy consumption to reach 170°C is 17.3MJ (5.6% bitumen), so that total energy consumption to make a tonne of mix is $0.944 \times 159.2 + 17.3 = 167.6$ MJ. Energy saving compared to hot mix is therefore $192.8 - 167.6 = 25.2$ MJ/tonne, ie 13.1%.

Emulsion-based mixes

The product Evotherm® is a proprietary cationic emulsion containing 70% bitumen which is stored at 80°C. It is mixed with aggregate heated to approximately 135°C (Hurley and Prowell 2006) (unlike cold mix where the emulsion is mixed with unheated aggregate).

Energy required to heat 1000kg of standardised aggregate from 10 to 135°C is 163.6MJ, (88.1% of the 185.8MJ needed to reach 160°C, ie a saving of 22.2MJ or 11.9%).

For 1000kg of asphalt mix we need 56kg of bitumen, which corresponds approximately to $57/0.7 = 80$ litres of emulsion.

Since emulsion is commonly produced in plant belonging to the same contractor as produces the asphalt, we need to include the energy used to produce the emulsion. This energy will depend, amongst other things, on the emulsifier plant used, the percentage of bitumen, the final target temperature of the product and the target size range of the emulsified bitumen particles, and a representative figure only can be given. Dorchie (2008) quotes an energy input figure provided by Eurobitume of 3490MJ/t for a 60% emulsion, ie approximately 3.49MJ/l. Holleran and Reed (1996) say that 567kJ is required to make a litre of bitumen emulsion. The energy to manufacture the emulsifier is 584kJ. Adding these gives a figure of 1151kJ or 1.151MJ to produce a litre of bitumen emulsion.

We are looking solely at manufacturing energy requirements for the asphalt, and so will take the 567kJ/l figure, which would give 45.4MJ input for the 80 litres used to produce a tonne of asphalt.

The total figure is thus $0.944 \times 163.6 + 45.4 \approx 199.8$ MJ/t which is greater than the 192.8MJ/t for hot mix, ie 3.6% more energy input is needed. This may be an underestimate, depending on the details of the proprietary emulsion used. It is interesting that at least one publication does report higher energy usage for manufacturing Evotherm® mix (Ursich 2008).

Foam mixes

The EAPA position paper on the use of warm mix asphalt (European Asphalt Pavement Association (EAPA 2009) indicates that for these mixes the asphalt mixing temperature reduced by 20–30°C. Bitumen will be heated to higher temperatures, as this encourages foaming. Thus, for the purpose of calculation we will take mixing temperature as 135°C and the bitumen temperature before foaming as 170°C.

To bring a tonne of the standardised aggregate from 10°C to 135°C requires 163.6MJ of energy, ie 88.1% of that needed to reach 160°C.

Including the energy needed to heat the bitumen to 170°C (17.3MJ), total energy to produce a tonne of asphalt becomes $0.944 \times 163.6 + 17.3 = 171.7\text{MJ}$, ie 21.1MJ or 10.9% savings.

The American firm Astec Industries claims on its website that with its 'double barrel green' process it is only necessary to heat the aggregate to 230 to 270°F, ie 110 to 132°C (Astec 2008). Presuming the aggregate is heated to 120°C gives us 150.3MJ (35.5MJ or 19.1% energy saving against 160°C) per tonne of aggregate, or $0.944 \times 150.3 + 17.3 = 159.2\text{MJ/tonne}$ of mix (33.6MJ/tonne, ie 17.4% energy saving per tonne of mix).

Low energy asphalt (LEA) processes

Process sequences

Olard, le Noan et al (2008) describe three different sequences employed for mixing coarse aggregate, fines, water and bitumen in the LEA process. The three sequences, along with representative temperatures, are described in section 2.5.2.3, and we use the labelling and temperatures from that section in the following calculations.

Energy expenditure – sequences A and B

To heat 650kg of coarse aggregate (1% water) from 10°C to 130°C: $0.65 \times 129.3 = 84.0\text{MJ}$. No further heat is added for the fine fraction. Therefore the energy saved on heating a tonne of aggregate, compared to hot mix, is $185.8 - 84.0 = 101.8\text{MJ}$, ie 54.8%.

For a tonne of mix with 5.6% bitumen we have a total energy requirement of $0.944 \times 84.0 + 17.3 = 96.6\text{MJ}$. The saving compared to hot mix is $192.8 - 96.6 = 96.2\text{MJ/tonne}$, ie 49.9%

Energy expenditure – sequence C

Heating all the aggregate from 10 to 100°C requires 84.5MJ/tonne. Following the approach of Olard, le Noan et al (2008) we assume a partial evaporation of 50% of the water in the dryer, which, referring to table A.1, requires $0.5 \times (132.5 - 84.5) = 24.0\text{MJ/tonne}$ of aggregate. The total energy input is therefore $84.5 + 24.0 = 108.5\text{MJ/tonne}$ of aggregate, with a saving against hot mix of $185.8 - 108.5 = 77.3\text{MJ/t}$, ie 41.6%.

For a tonne of mix with 5.6% bitumen we have a total energy requirement of $0.944 \times 108.5 + 17.3 = 119.7\text{MJ/tonne}$ of mix. The saving compared to hot mix is $192.8 - 119.7 = 83.1\text{MJ/tonne}$, ie 43.1%.

