CHAPTER II
THEORETICAL BACKGROUND AND LITELATURE REVIEW

2.1 Asphalt

Asphalt is the heaviest product of crude oil refinery. It is a viscous liquid or semi-solid which has black or brown color. Structure of asphalt is a chain of hydrocarbon composed of various organic substances as show in Figure 2.1. When asphalt was improved its properties, it will have the chemicals and gases resistant property, climate change resistant property, impact resistant property and stiffness or flexible in various temperature.

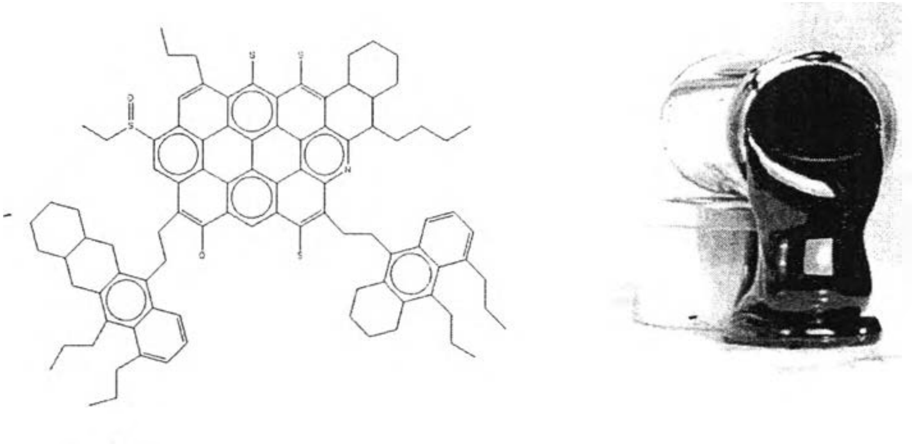


Figure 2.1 Structure and color of asphalt (Amin *et al.*, 2011).

Asphalt or bitumen can sometimes be confused with "tar", which is a similar black, thermoplastic material produced by the destructive distillation of coal. During the early and mid-20th century when town gas was produced, tar was a readily available product and extensively used as the binder for road aggregates. The addition of tar to macadam roads led to the word tarmac, which is now used in common parlance to refer to road-making materials. However, since the 1970s, when natural gas succeeded town gas, asphalt (bitumen) has completely overtaken the use of tar in these applications. Other examples of this confusion include the La Brea Tar Pits and the

Canadian tar sands. Pitch is another term mistakenly used at times to refer to asphalt/bitumen, as in Pitch Lake.

Natural deposits of asphalt include lake asphalts (primarily from the Pitch Lake in Trinidad and Tobago and Lake Bermudez in Venezuela), Gilsonite, the Dead Sea, bituminous rock and tar sands. Asphalt was mined at Ritchie Mines in Macfarlan in Ritchie County, West Virginia in the United States from 1852 to 1873. Bituminous rock was mined at many locations in the United States for use as a paving material, primarily during the late 1800s.

The substance is completely soluble in carbon disulfide, and composed primarily of a mixture of highly condensed polycyclic aromatic hydrocarbons; it is most commonly modeled as a colloid, with asphaltenes as the dispersed phase and maltenes as the continuous phase (though there is some disagreement amongst chemists regarding its structure). One writer stated although a "considerable amount of work has been done on the composition of asphalt, it is exceedingly difficult to separate individual hydrocarbon in pure form", and "it is almost impossible to separate and identify all the different molecules of asphalt, because the number of molecules with different chemical structure is extremely large".

Most natural bitumen contains sulfur and several heavy metals, such as nickel, vanadium, lead, chromium, mercury, arsenic, selenium, and other toxic elements. Bitumen can provide good preservation of plants and animal fossils. Asphalt can be separated from the other components in crude oil (such as naphtha, gasoline and diesel) by the process of fractional distillation, usually under vacuum conditions. A better separation can be achieved by further processing of the heavier fractions of the crude oil in a de-asphalting unit, which uses either propane or butane in a supercritical phase to dissolve the lighter molecules which are then separated. Further processing is possible by "blowing" the product: namely reacting it with oxygen. This makes the product harder and more viscous.

The primary use of asphalt is in road construction where it is used as the glue or binder mixed with aggregate particles to create asphalt concrete. Its other main uses are for bituminous waterproofing products, including production of roofing felt and for sealing flat roofs.

2.1.1 Asphalt Application

Asphalt or Bituminous pavements are manufactured using a wide variety of methods and materials. Some are ready-made mixes manufactured in large industrial mixing plants and others are produced by mixing the ingredients on site. Their common feature is that they all contain natural soils or crushed aggregate mixed with different formulae of bitumen. Flexible pavements for high volume roads, such as national highways, commonly consist of several layers of bitumen stability pavements. For rural roads, where traffic loads are much less, the thickness of the bituminous pavement is significantly reduced. Often, only a thin surface layer is laid over a base course consisting of natural gravels or crushed and screened stone aggregate.

Most bituminous surface seals consist of a coat of bitumen in which stone aggregate, gravel or sand has been embedded. The main function of this surface layer is to provide resistance to the abrasive wear of the traffic and stop water from penetrating into the road pavement, while the base course underneath provides the necessary load bearing strength of the road. Some bituminous pavements however, such as penetration macadam and some hot mix asphalts, can perform both as surface treatments and also contribute to the load bearing capacity of the road.

Asphalt needs to meet specific performance requirements first in relation to when it is applied to a road surface and secondly once traffic is allowed onto the road after completion of works. During construction the bitumen needs to be soft enough to (i) mix with the selected aggregate and (ii) adequately viscous to spread on a road surface. Once it has been applied, the performance requirements change to a rather opposite feature in which the objective is to produce a hard and durable surface which resists the effects of adverse weather conditions and traffic, Figure 2.2 shows the cross section of the road (Johannessen, 2008).

The asphalt pavement is showed in Figures 2.3, 2.4 and 2.5. It can be divided into the following steps.

1) Surface Preparing
    - Prime coat
    - Tack coat
2) Surface Pavement

  - Hot-Mixed Asphalt or Asphaltic Concrete
  - Cold-Mixed or Cold Mixed Asphalt
3) Surface Dressing
  - Single Surface Treatment (Chip Seal)
  - Double Surface Treatment (DBST)
  - Slurry Seal / Para Slurry Seal
  - Cape Seal (Chip Seal + Slurry Seal) / Para Cape Seal
4) Pavement Recycling
5) Patching or Deep Patching

Procedures of pavement have 5 steps

1) Tack coat
2) Laying
3) Steel wheeled Tandem roller compaction
4) Pheumatic-tired compaction
5) Let it cool and then opened to traffic

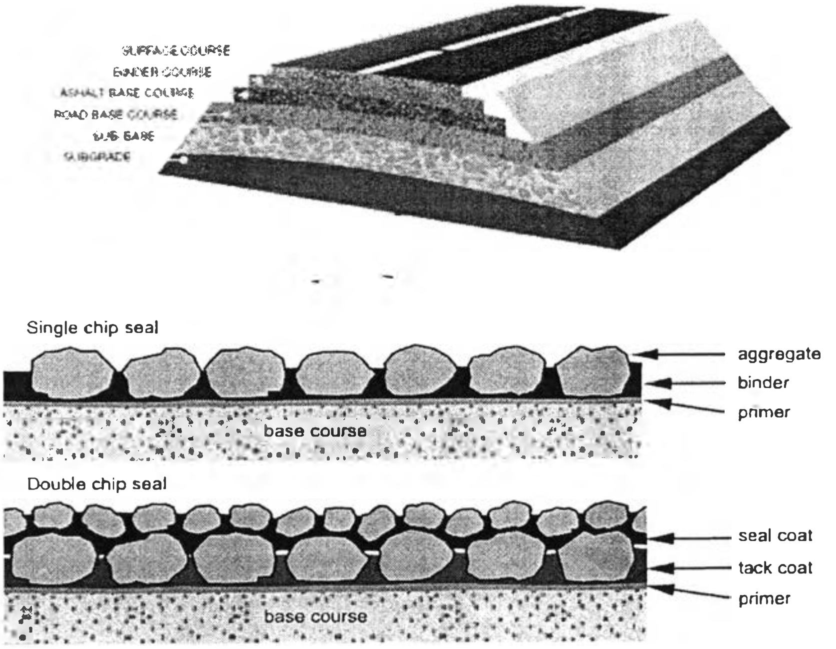


Figure 2.2 The cross section of the road (Johannessen, 2008).

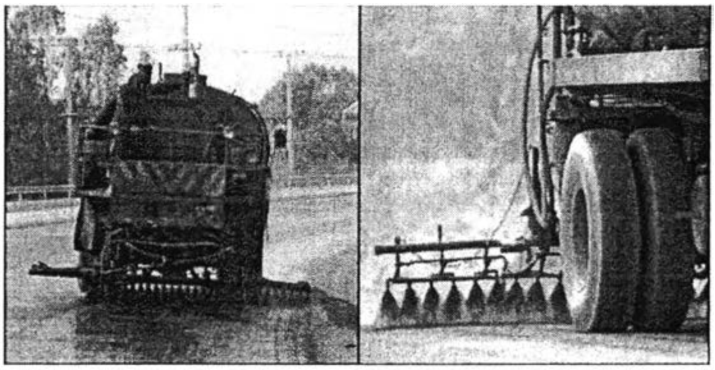


Figure 2.3 Prime coat method.

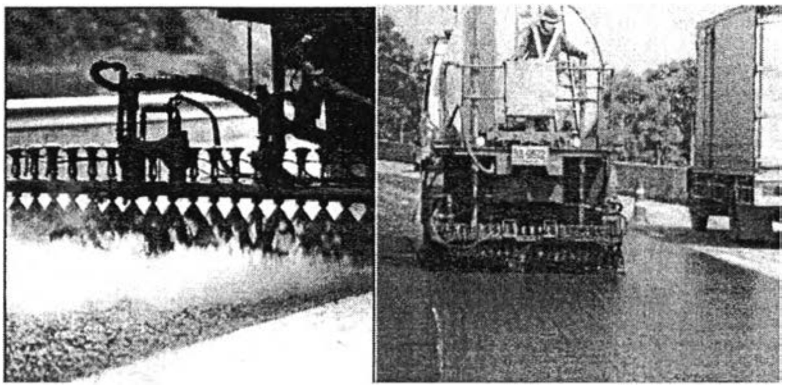


Figure 2.4 Tack coat method.

2.2 Hot-Mixed Asphalt (HMA)

Hot-mixed asphalt (HMA) is used primarily as paving material and consists of a mixture of aggregate and liquid asphalt cement, which are heated and mixed in measured quantities. Hot-mixed asphalt facilities can be broadly classified as either drum-mixed plants or batch mix plants, according to the process by which the raw materials are mixed. In a batch-mixed plant (see Figure 2.6), the aggregate is dried first then transferred to a mixer where it is mixed with the liquid asphalt. In a drum-mixed plant, a rotary dryer serves to dry the aggregate and mix it with the liquid asphalt cement. After mixing, the HMA generally is transferred to a storage bin or silo, where it is stored temporarily. From the silo, the HMA is dump into haul trucks, which transport the material to the job site.

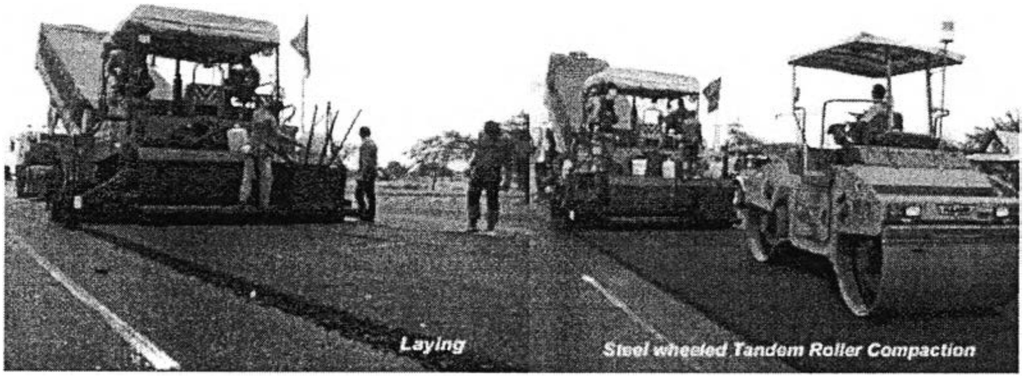


Figure 2.5 Laying and Steel wheeled Tandem roller compaction.

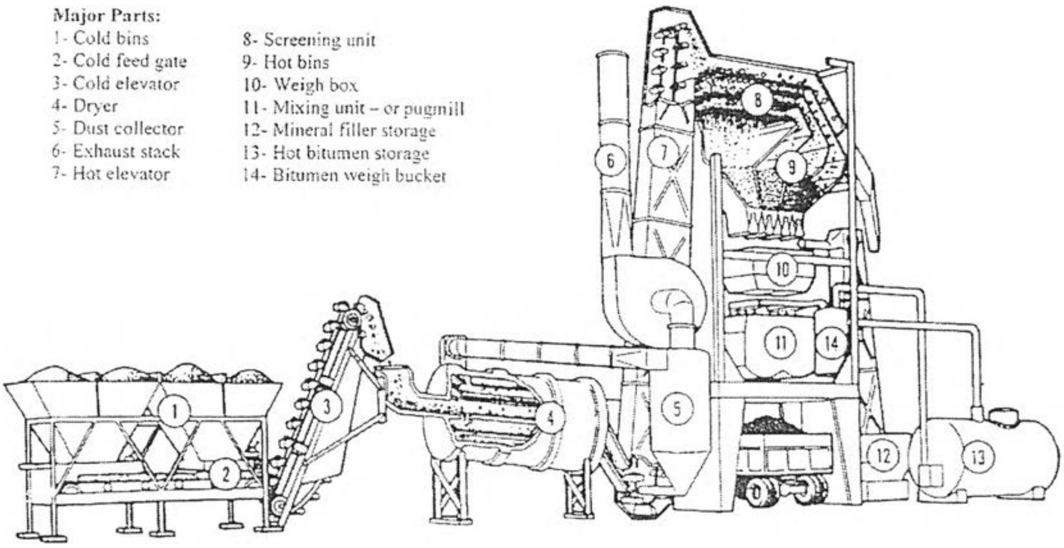


Figure 2.6 Details hot-mixed asphalt plant (Aditya, 2011).

The primary emission sources associated with HMA production are the dryers, hot bins, and mixers, which emit particulate matter (PM) and a variety of gaseous pollutants. Other emission sources found at HMA plants include storage silos, which temporarily hold the HMA; truck load-out operations, in which the HMA is loaded into trucks for hauling to the job site; liquid asphalt storage tanks; hot oil heaters, which are used to heat the asphalt storage tanks; and yard emissions, which consist of fugitive emissions from the HMA in truck beds. Emissions also result from vehicular traffic on paved and unpaved roads, aggregate storage and handling operations, and vehicle exhaust. The PM emissions associated with HMA production include the criteria pollutants PM-10 (PM less than 10 micrometers in aerodynamic diameter) and $PM_{2.5}$, hazardous air pollutant (HAP) metals, and HAP organic compounds. The gaseous emissions associated with HMA production include the criteria pollutants sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOC), as well as volatile HAP organic compounds.

2.3 Warm-Mixed Asphalt (WMA)

2.3.1 Background of Warm-Mixed Asphalt

Warm-mixed asphalt (WMA) is the asphalt paving technologies that allow a reduction in the temperatures at which asphalt mixes are produced and placed. These technologies tend to reduce the viscosity of the asphalt and provide for the complete coating of aggregates at lower temperatures. WMA is produced at temperatures 20 to 55 °C (35 to 100 °F) lower than typical hot-mixed asphalt (HMA) (Kristjansdottir, 2006).

WMA can be conveniently classified by the degree of temperature reduction compared to conventional HMA. This is illustrated in Figure 2.7, which shows the typical ranges in mix temperature, from cold-mixed asphalt (CMA) to conventional hot-mixed asphalt (HMA). It also shows how the consumption of fuel increases in order to produce mixes at higher temperatures. In terms of the manufacturing temperature used to produce them: (i) cold-mixed asphalt (CMA) manufactured at a temperature lower than 60 °C; (ii) half-warm-mixed asphalt (HWMA) manufactured at less than 100 °C, normally at 70-95 °C; (iii) warm-mixed asphalt (WMA) manufactured at temperatures of 110-140 °C (Rubio *et al.*, 2012).

2.3.2 Warm-Mixed Asphalt Technologies

WMA technologies can also be classified by the technology used, and divides them into three categories: (i) foaming processes (subdivided into water-containing and water-based processes); (ii) addition of organic additives (i.e. Fischer-

Tropsch synthesis wax, fatty acid amides, and Montan wax); (iii) addition of chemical additives (usually emulsification agents or polymers i.e. Evoterm). Table 2.1 (ZAUMANIS, 2010) shows the products generally used for WMA.

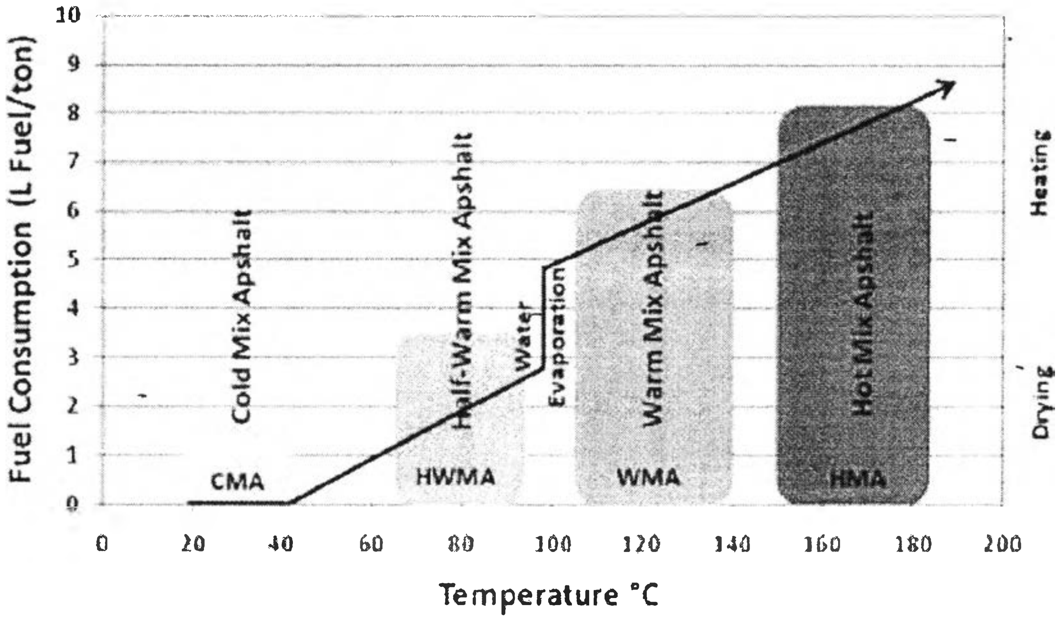


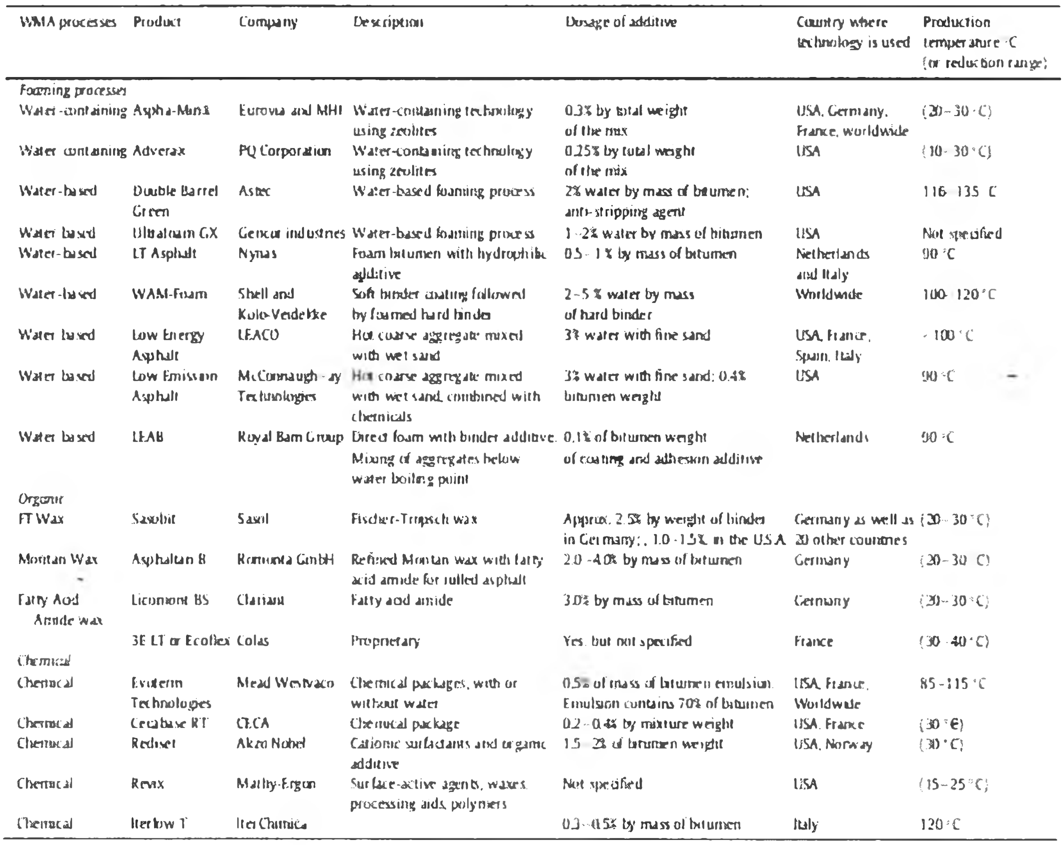
Figure 2.7 Asphalt-mixed classifications according to manufacturing temperature (Rubio *et al.*, 2013).

2.3.2.1 Foaming Process

Bitumen foaming techniques is generally made by adding a small amount of cold pulverized water into preheated bitumen. The water vaporizes and the liberated steam is encapsulated within bitumen, resulting in a temporary expansion of its volume together with a reduction of its viscosity. But when the water turns to steam, and increases the volume of the bitumen and reduces its viscosity just for a short period until the material has cooled. After that the foam will collapses and the bitumen behaves as a normal binder.

Although the basic process is the same for most of these products and technologies, the way in which water is added to the binder can vary. This means that foaming processes can either be water-based (direct method technologies) or water-containing (indirect method technologies).

Table 2.1 Products used in warm-mixed technologies (Rubio *et al.*, 2012)



WMA processes	Product	Company	Description	Dosage of additive	Country where technology is used	Production temperature °C (or reduction range)
Foaming processes						
Water-containing	Aspha-Min®	Eurovia and MHI	Water-containing technology using zeolites	0.3% by total weight of the mix	USA, Germany, France, worldwide	(20–30 °C)
Water containing	Adverax	PQ Corporation	Water-containing technology using zeolites	0.25% by total weight of the mix	USA	(10–30 °C)
Water-based	Double Barrel Green	Astec	Water-based foaming process	2% water by mass of bitumen; anti-stripping agent	USA	116–135 °C
Water based	Ultrafoam GX	Gencor industries	Water-based foaming process	1–2% water by mass of bitumen	USA	Not specified
Water-based	LT Asphalt	Nynas	Foam bitumen with hydrophilic additive	0.5–1 % by mass of bitumen	Netherlands and Italy	90 °C
Water-based	WAM-Foam	Shell and Kolo-Veidekke	Soft binder coating followed by foamed hard binder	2–5 % water by mass of hard binder	Worldwide	100–120 °C
Water based	Low Energy Asphalt	LEACO	Hot coarse aggregate mixed with wet sand	3% water with fine sand	USA, France, Spain, Italy	< 100 °C
Water based	Low Emission Asphalt	McConnaugh-ay Technologies	Hot coarse aggregate mixed with wet sand, combined with chemicals	3% water with fine sand; 0.4% bitumen weight	USA	90 °C
Water based	LEAB	Royal Bam Group	Direct foam with binder additive. Mixing of aggregates below water boiling point	0.1% of bitumen weight of coating and adhesion additive	Netherlands	90 °C
Organic						
FT Wax	Sasobit	Sasol	Fischer-Tropsch wax	Approx. 2.5% by weight of binder in Germany; 1.0–1.5% in the USA	Germany as well as 20 other countries	(20–30 °C)
Montan Wax	Asphaltan B	Romonta GmbH	Refined Montan wax with fatty acid amide for rolled asphalt	2.0–4.0% by mass of bitumen	Germany	(20–30 °C)
Fatty Acid Amide wax	Licomont BS	Clariant	Fatty acid amide	3.0% by mass of bitumen	Germany	(20–30 °C)
	3E LT or Ecoflex	Colas	Proprietary	Yes, but not specified	France	(30–40 °C)
Chemical						
Chemical	Evotherm Technologies	Mead Westvaco	Chemical packages, with or without water	0.5% of mass of bitumen emulsion. Emulsion contains 70% of bitumen	USA, France, Worldwide	85–115 °C
Chemical	Cecabase RT	CECA	Chemical package	0.2–0.4% by mixture weight	USA, France	(30 °C)
Chemical	Rediset	Akzo Nobel	Cationic surfactants and organic additive	1.5–2% of bitumen weight	USA, Norway	(30 °C)
Chemical	Revix	Mathy-Ergon	Surface-active agents, waxes, processing aids, polymers	Not specified	USA	(15–25 °C)
Chemical	Iterlow T	Iteri Chimica		0.3–0.5% by mass of bitumen	Italy	120 °C

2.3.2.1.1 Water-containing Technologies

Water-containing technologies are the water indirect method technologies, which use synthetic zeolite to produce the foaming process. Product of this process is composed of aluminosilicates of alkali metals, and has been hydro-thermally crystallized. The crystallization is approximately 20% water, which is released from the zeolite structure as the temperature rises. This causes a microfoaming effect in the asphalt mix, which lasts about 6-7. The structure of the zeolites has large air voids where cations and even molecules or cation groups (such as water) can be hosted. Their ability to lose and absorb water without damaging the crystalline structure is the main characteristic of this silicate framework (Rubio *et al.*, 2012).

2.3.2.1.2 Water-based Technologies

Water-based technologies are the water direct method technologies, which use water in a more direct way. This means that the water needed to produce the foaming effect is injected directly into the hot binder flow usually with special nozzles. As the water rapidly evaporates, this produces a large volume of foam that slowly collapses. This category can be subdivided into the types of product used to make the mix:

- The first mixes, must have equipment for injecting water into the hot binder. Several nozzles are used to inject the cold water to microscopically foam the binder (i.e. Double Barrel Green, Ultrafoam GX, LT Asphalt)

- The second mixes is a two-component binder system (also known as a two-phase method) that feeds a soft binder and a hard foamed binder at different times into the mixing cycle during production. The soft bitumen is first mixed with the aggregate to pre-coat it. Then the hard bitumen is added to the mixture, which has been foamed by the previous injection of cold water in a quantity ranging from 2% to 5% of the mass of the hard binder. This combination of soft binder and foaming of the hard binder, along with the foaming of the hard bitumen, reduces mix viscosity to provide the necessary workability (i.e. WAM Foam) (Rubio *et al.*, 2012).

In this instance the foaming results in an improved coating and workability of the mix which can subsequently allow a decrease in the mix temperature by approximately 30°C with equivalent compaction performance. But its duration is limited. This means that the mix must be spread and compacted soon after production.

2.3.2.2 Organic Additives

Organic or wax additives are used to achieve the temperature reduction by reducing viscosity of binder. The processes show a decrease of viscosity above the melting point of the wax making it possible to produce asphalt concrete mixes at lower temperatures. After crystallization these additives solidify into microscopically small and uniformly distributed particles, which increase the stiffness of the binder in the same way as fiber-reinforced materials and asphalt's resistance against deformation. The type of wax must be selected carefully so that the melting point of the wax must be higher than expected in service temperatures and to minimize embrittlement of the asphalt at low temperatures. This type of process was developed at the end of 1980s, and has been in use ever since. It has given rise to three technologies, which differ in the type of wax used to reduce viscosity: Fischer-Tropsch wax, fatty acid amide, and Montan wax.

2.3.2.2.1 Fischer-tropsch Wax

Fischer-Tropsch paraffins are long-chain aliphatic hydrocarbons which are produced from syngas (carbon monoxide and hydrogen) under a high pressure catalytic process. FT-molecules have a different chain length than paraffins that are naturally found in mineral oil. This explains why FT-paraffins have different physical properties and why they cannot be compared with naturally occurring bituminous waxes. FT-paraffins are completely soluble in bitumen at temperatures above 115 °C. They form a homogeneous solution with base bitumen on stirring and produce a marked reduction in the bitumen's viscosity during its liquid state. During cooling the FT-paraffins crystallize and form crystallites in the bitumen. This in turn, increases asphalt stability and its deformation resistance.

The difference between naturally occurring bituminous waxesand F-T waxes resides in their structure and physical properties. More specifically, the main difference is their much longer chain lengths and fine crystalline structure. Research has shown that these waxes have good oxidation and ageing stability, and can be stored indefinitely (Hurley *et al.*, 2005).

2.3.2.2.2 Fatty Acid Amide

Fatty acid amides are synthesized long chain aliphatic hydrocarbons. They are manufactured synthetically by causing amines to react with fatty acids. Fatty acid amide molecules have a different chain length than paraffins naturally found in mineral oil. This explains why fatty acid amides have different physical properties and why these amides cannot be compared with naturally occurring bituminous waxes.

Fatty acid amides are completely soluble in bitumen at temperatures above 140°C. When stirring the mix they form a homogeneous solution with the base bitumen and produce a marked reduction in the bitumen's viscosity during its liquid state.

During cooling the fatty acid amides crystallize and form crystallites in the bitumen, thus increasing asphalt stability and its deformation resistance.

2.3.2.2.3 Montan Wax

The difference between naturally occurring bituminous waxes and F-T waxes resides in their structure and physical properties. Montan wax (lignite wax) is extracted from special waxy lignite. In chemical terms, Montan wax consists mainly of fossil fatty acid esters. It is a combination of nonglyceride long-chain carboxylic acid esters, free long-chain organic acids, long-chain alcohols, ketones, hydrocarbons, and resins. Since the melting point of this wax in its pure state is approximately 75°C, it is often blended with materials with a higher melting temperature such as amide waxes. Research has shown that these waxes have good oxidation and ageing stability. and can be stored indefinitely (Hurley *et al.*, 2005).

2.3.2.3 Chemical Additives

Chemical additives are the third type of WMA technology that is commonly used. A variety of chemical packages are used for different products. They usually include a combination of emulsification agents, surfactants, polymers and additives to improve coating, mixture workability, and compaction, as well as adhesion promoters (anti-stripping agents). The added amount and temperature reduction depends on the specific product used. The chemical additive package is used either in the form of an emulsion or added to bitumen in mix production process and then mixed with hot aggregate. This results in relatively minor modifications needed to the asphalt plant or to the mix design process.

These WMA technologies utilize chemical additives that have little effect on binder rheological properties. The products may be supplied in pellet, powder or liquid form, and then mixed into the binder or added direct to the mixer. They work by a surfactant effect that enhances the spreading of the binder film over the aggregate by reducing surface tension, resulting in a lubricating effect on the mix even at lower temperatures. Some of the surfactants used also have an adhesion promoting effect and products can contain additives that have a binder stiffening effect at service temperatures. Other technologies falling into this class are formulated as high residual bitumen content emulsions that contain agents to improve aggregate coating and workability, as well as adhesion promoters. They are in the form of emulsions these technologies can be stored at much lower temperatures than other binders used in the production as asphalt, at around 80°C. The water in the emulsion vaporizes when it is mixed with the heated aggregate, forming a foamed binder with a significantly increased volume. This enhances aggregate coating at lower temperatures in a similar way to the "water technologies" while the additives modify other mix properties.

2.3.3 Benefits and Drawbacks of Warm Mix Asphalt

The specific benefits of WMA depend on the process being considered. For this reason, it is difficult to group all WMA processes into one category and state that their features are superior or inferior to those of HMA (Button, 2008) However, the main benefits/advantages of using WMA over HMA are the reduction in production and compaction temperature achieved by WMA technologies brings many potential benefits. Fewer emissions, lower fuel consumption, longer haul distances, and better working conditions are the most significant advantages mentioned. Even though the lower temperatures in WMA are initially a very promising aspect of this technology, they are also a source of concern. Such concerns mainly pertain to the performance and implementation of WMA, especially in reference to specifications and quality controls.

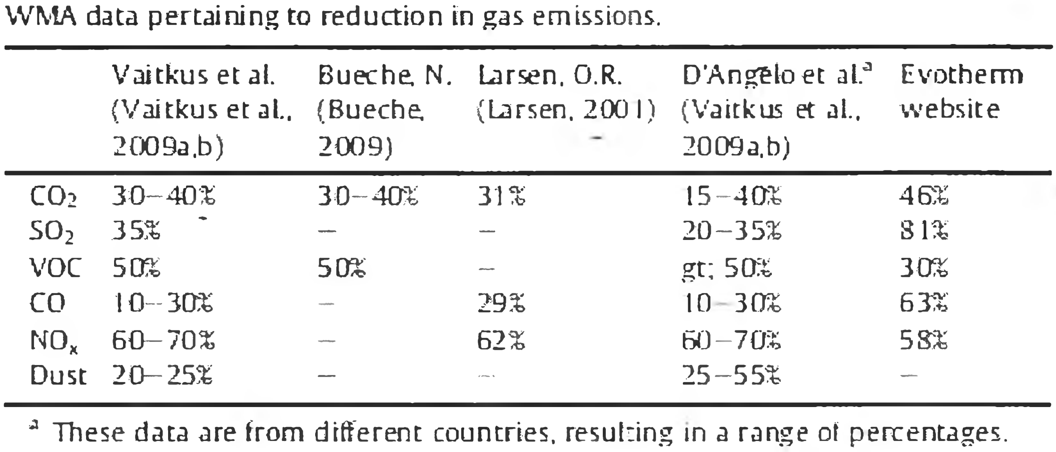
2.3.3.1 Benefits of Warm Mix Asphalt

2.3.3.1.1 Environmental Benefits

The main of environmental benefits of warm mix asphalt are lower plant emissions and fumes, and can be recycling scrap tires. Relate to the temperature reduction in WMA, which produces an enormous drop in emissions and fumes. Consequently, greenhouse gases are lower for WMA than for HMA. In this respect, Table 2.2 compares the research results obtained in various studies.

Furthermore, the reduction of emissions and fumes is also beneficial for workers (Kristjansdottir, 2006), who are negatively affected by exposure to the fumes produced by the asphalt paving process. When there is less exposure, as occurs with WMA technologies, this improves working conditions. For paving projects that are not in open air (e.g. tunnels), worker exposure to emissions is magnified. Thus, WMA and its reduced emissions are especially desirable for such situations. A further consideration is that lower mix temperatures also contribute to a more comfortable working environment, and this might even be a factor that retains workers for a longer time at their jobs (Rubio *et al.*, 2012).

Table 2.2 WMA data pertaining to reduction in gas emissions (Rubio *et al.*, 2012)



WMA data pertaining to reduction in gas emissions.

	Vaitkus et al. (Vaitkus et al., 2009a,b)	Bueche, N. (Bueche, 2009)	Larsen, O.R. (Larsen, 2001)	D'Angelo et al.[a] (Vaitkus et al., 2009a,b)	Evotherm website
CO_2	30–40%	30–40%	31%	15–40%	46%
SO_2	35%	–	–	20–35%	81%
VOC	50%	50%	–	gt; 50%	30%
CO	10–30%	–	29%	10–30%	63%
NO_x	60–70%	–	62%	60–70%	58%
Dust	20–25%	–	–	25–55%	–

[a] These data are from different countries, resulting in a range of percentages.

The lower mixing temperatures required to manufacture WMA consumes less energy for heating during asphalt production. The reduced consumption of burner fuel conserves non-renewable fossil fuels and reduces greenhouse gas emissions. Investigations carried out in several countries show significant reductions in emissions of carbon dioxide (CO_2) and nitrous oxide (NOx), while the emissions of sulphur dioxide (SO_2) and VOC's (volatile organic compounds) varied above and below those of HMA.

Although most of WMA additives are produced specially for WMA production, some such as Fischer-Tropsch waxes are produced as a by-product of the Fischer-Tropsch process and if not used may become a waste material. So these by-products can reused and has a direct environmental benefit of reducing waste materials and also pollution from the production of other WMA specific additives. The increased potential for recycling RA in WMA over HMA is discussed below as an economic benefit but is listed here also as an environmental benefit as the recycling of RA reduces the volume of waste material that would otherwise have to be disposed of; it extracts the highest value from the RA and reduces the quantity of new (non-renewable resources) aggregate and bitumen required for new asphalt layers.

2.3.3.1.2 Economic Benefits

The mainly economic benefits of WMA are reduced energy consumptions and financial costs, which depend on the type of energy used in the production process, its cost, and pollution potential. In most countries, energy costs are relatively high, and thus any reduction in this respect is highly valued by the asphalt producer. More over if stricter emission standards were implemented and enforced WMA would have an even greater economic potential. Broadly speaking, WMA can reduce energy consumption amounts to 60-80% of HMA energy consumption (Kristjansdottir, 2006). However, these economic benefits also bring added costs resulting from the modifications needed in the plants. WMA temperature reduction is also the source of another possible cost reduction because there may be less wear on the asphalt plant (EAPA, 2010).

2.3.3.1.3 Paving Benefits

The mainly paving benefits of WMA are Improve workability and compaction efficiency, longer haul distances and quicker turnover to traffic due to shorter cooling time. The other benefits that derive from these are discussed below.

- Compaction aid

The improved workability provided by WMA technologies improves mix cohesion and act as a compaction aid where stiff mixes would be otherwise difficult to compact.

- Improved workability for hand work

WMA technologies improve mix cohesion and compaction that is beneficial where hand work is required such as at intersections, widening, around manholes or for patching.

- Paving in cold weather

Climatic conditions in South Africa do not pose the same cold weather paving limitations as countries at higher latitude, nevertheless there are times when low winter temperatures hamper paving operations.

Due to the lower mix and paving temperatures, WMA's slower rate of cooling and longer "compaction window" provide significant advantages over HMA when transporting and paving asphalt in cold weather.

In regions of the country that experience very cold winters, the paving season can be extended using WMA.

- Paving at night

The lower WMA compaction temperatures and rate of cooling increase the opportunities for undertaking night work when ambient and road temperatures are lower than during the day and provides great advantages especially for busier roads where traffic can be economically accommodated on fewer lanes only at night when traffic volumes are significantly lower.

- Increased haulage time/distance

The slower rate of cooling and longer compaction window allows WMA to be hauled for longer than HMA. This provides the advantage of hauling longer distances, or where in the urban settings traffic congestion is expected, extended haulage times.

In more extreme situations further advantage can be taken by manufacturing mix using WMA technologies but at HMA temperatures to enable substantially longer haulage distances or times.

- Reduced binder aging

The reduced temperatures of WMA are expected to reduce binder aging during production and paving and result in improved flexibility and resistance to fatigue and thermal cracking in the asphalt layers. It is speculated that this will improve pavement performance and increase the period between maintenance interventions; thus saving money by reducing lifecycle costs and using less non-renewable resources. The extent of the reduced lifecycle costs will have to be verified by long-term pavement performance measurement. Ingredients of some WMA additives have an additional anti-aging effect.

- Siting plants closer to the work

Suitable sites for asphalt plants close to urban road networks, such as those found in major towns and cities are often difficult to find, due to plant emission requirements. Plants have to be situated far from these areas, making for long haulage distances. The lower emissions that can be expected from WMA means that asphalt plants can be located closer to the urban jobsites, thus reducing haulage distance. Also the decrease in emissions represents a significant cost saving, considering that 30% to 40% of overhead costs at the asphalt plant can be attributed to emission control. Also, with the vehicles transporting the mix over shorter distances, their fuel consumption and emissions are reduced, further contributing to the savings.

2.3.3.2 Drawbacks of Warm Mix Asphalt

2.3.3.2.1 Rutting

Rutting is mainly caused by the less ageing of the binder because of the lower production temperatures, as well as moisture susceptibility of WMA mixes. This can result in the premature rutting of the pavement surface (ZAUMANIS, 2010).

2.3.3.2.2 Cost Effectiveness

Although WMA promises a significant reduction in energy consumption, initial costs, in addition to royalties, could discourage contractors. Unless stricter emission regulations are enforced, contractors will probably not use these technologies, solely for their other benefits (Kristjansdottir, 2006). Indeed, the initial cost of WMA could be the greatest obstacle to overcome. Furthermore, other costs, such as recurrent ones or royalties, also have to be considered. This initial cost varies depending on the technology used. For example, the use of WMA technology requires additives (a recurrent cost) and asphalt plant modifications, which requires a capital investment. These technologies could bring important savings if a better long-term performance is achieved as a result of the less ageing of the binder during production. Nevertheless, this has yet to be proven as WMA has not been employed for a sufficiently long time period for a real evaluation of its cost effectiveness (STACEY *et al.*, 2008).

2.3.3.2.3 Moisture Susceptibility

The lower compaction temperature used when producing warm asphalt may increase the potential for moisture damage, as established in the studies carried out by Hurley (Hurley *et al.*, 2005). Moisture damage appears to have two causes. First, lower mixing and compaction temperatures can result in incomplete drying of the aggregate.

To prevent moisture susceptibility, proper mix design is thus essential. Of the many ways to prevent stripping in a pavement, the use of anti-stripping agents (ASAs) is the most common method. One of the most frequently used ASAs is hydrated lime. According to previous research studies, the addition of the right anti-stripping agents can reduce potential moisture damage (Xiao *et al.*, 2010). The second cause stems from the use of these ASAs. Since liquid ASAs are blended with the binder, and then mixed with aggregate and the water-bearing additive, chemical reactions between these components may occur at a high mixing temperature (around 110°C), which may result in a loss of bond in a mixture (Smith, 2006). The addition of RAP to WMA mixtures can improve moisture sensitivity performance and also prevent rutting (Hill, 2011).

2.3.3.2.4 Long Term Performance

Evidently if WMA does not perform well throughout its life cycle, there will be no long-term environmental benefits or energy savings. Due to the relative newness of these products, field test sections are still few in number, and they also have a short life (seven years in the USA and over ten years in certain European countries). For this reason, it is not as yet possible to talk about long term performance. To date, in the USA no significantly negative long term performance has been reported (Chowdhury *et al.*, 2010) and in Europe the trial sections of WMA have performed as well as or better than HMA overlays (John D'Angelo *et al.*, 2008). It is important to highlight that, whereas in the USA tests have been performed by public organisation (Departments of Transportation), in Europe they have been carried out by the private companies that market the products. Evidently, this means that at least in certain cases, the evaluation of WMA technologies is somewhat less objective.

2.3.3.2.5 Environmental Pollution Effects of WMA Additives

Even though certain WMA manufacturing techniques include the use of chemical additives, it is still uncertain whether they are a potential source of pollution.

2.3.3.2.6 Quantitative Life Cycle Analysis (QLCA)

Evidently, a QLCA is needed in order to assess pavement sustainability and promote WMA technologies (Miller, 2010). As its name implies, such an analysis would consider the entire life cycle of a product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal. The application of LCA in the construction of asphalt pavements is relatively recent, as underlined by Huang (Huang *et al.*, 2009) in his study. However, it would allow companies to measure and compare products and processes, which would ultimately contribute to the development of technologies characterized by cleaner production.

2.4 Reclaimed Asphalt Pavements (RAP)

The re-use and recycling of reclaimed asphalt pavement started in 1955-1958. Surface layers were recycled in a primitive way with addition of oil, and then the energy crisis in 1973-1974 made the recycling of asphalt seriously started because of bitumen saving. But now the recycling of asphalt was widespread in every country, which comes from the results of energy crisis, climate change problem and the awakening of environmental conservation.

The materials present in old asphalt pavements may have value even when the pavements themselves have reached the ends of their service lives. Recognizing the value of those existing aggregate and asphalt resources, agencies and contractors have made extensive use of Reclaimed Asphalt Pavements (RAP) in producing new asphalt pavements for decades. Use of RAP has proven to be economical and environmentally sound. In addition, mixtures containing RAP have, for the most part, been found to perform as well as virgin mixtures.

Old asphalt pavements can be milled up and recycled into new mixtures for the same project or stockpiled for later use. Some countries as show in Table 2.3, such as Germany, allow the use of a higher percentage of RAP when it is reused on the same project on the presumption that it may be more consistent than materials from mixed stockpiles. The value attributed to the RAP should take into account the costs of transportation, handling, stockpiling, processing and testing (Rebecca *et al.*, 2000).

In the last decades, recycling of reclaimed asphalt has become more widespread. So below are the three main methods for manage the end of service asphalt.

1) Recycling asphalt, by adding the reclaimed asphalt to new asphalt mixes, with the aggregates and the old bitumen performing the same function as in their original application.
2) Re-using asphalt, by re-use the utilization of reclaimed asphalt as foundation, fill or base course material, with the recovered aggregate and bitumen performing a lesser function than in the original application.
3) Disposing asphalt, by landfill, which is not popular in the present because of environmental impact.

The use of RAP in the present pavements is desired because of the following.

1) The use of RAP is economical and can help to offset the increased of initial costs.
2) The use of RAP conserves natural resources and minimizing environmental impact.
3) The use of RAP contributes to sustainability.
4) The use of RAP avoids landfill and a burden for future.
5) If not reusing RAP could cause disposal problems and increased costs.
6) It good for the image of the industry.

2.4.1 Reuse and Recycling of Asphalt Techniques

The recycling processes can be divided into two major methods: hot or cold techniques. These can be further sub-divided into central plant or in-situ recycling. Central plant recycling (or "offsite recycling") consists in removing the material from the site to a plant located elsewhere which recycles the reclaimed asphalt in order to re-use it either on the original project or on other projects. In-situ recycling allows the reclaimed material to be incorporated directly back into the new asphalt pavement under construction or maintenance. The choice of process will depend on several factors by following:

1) The proximity of a suitable recycling plant.
2) The nature, quantity and quality of the reclaimed asphalt.
3) The amount and type of possible contaminants within the reclaimed material.
4) The programmed duration of construction.
5) The availability of space for interim storage of reclaimed asphalt prior to recycling and the engineering performance required from the new pavement.

Table 2.3 Reused asphalt in Europe 2011 (EAPA, 2010)

Country	available reclaimed asphalt (tonnes)	% of available reclaimed asphalt used in			
		hot and warm recycling	half warm recycling	cold recycling	unbound layers
Austria	550.000	90		5	5
Belgium	1.500.000	65			
Czech Republic	1.500 000	14	0	35	15
Denmark	600.000	80			20
France	7.080.000	45			
Germany	16.000.000	84			16
Hungary	64.882	100	0	0	0
Ireland	100.000	40	0	0	
Italy	11 000.000	20			
Luxembourg	190.000	95	0	5	
Netherlands	4.000.000	83		15	
Norway	726.000	18		0	62
Portugal	2.000	60	0	5	15
Romania	13.000	60	12	15	5
Spain	1.350.000	73		10	17
Sweden	1.100.000	70	5	5	15
Switzerland	1.750.000	51	18	19	10
Turkey	2.809.000	23			77

For all options, it is important to be able to determine the consistency of the source of reclaimed asphalt. To achieve the highest levels of recycling it is necessary to either confirm the lack of variability in the feedstock or to have precise data on its range of properties (Pedersen *et al.*, 2005).

2.4.1.1 Central Plants Recycling

- Batch mixing plant (cold) recycling
- Batch mixing plant (hot) recycling
- Drum mixer plant (hot) recycling
- Cold cycling

The recycling techniques include "cold" and "hot" methods. For all methods the broken up material must be crushed and screened into correct sizes before further processing.

Cold milling of asphalt pavements leads to material (RAP) that can be used in the recycling process without further processing (crushing). "Cold" methods refer to the addition of the reclaimed asphalt pavement (RAP) either at the discharge of the dryer into the hot elevator, or in the aggregates weighing scale, in these cases. the material is heated by the virgin aggregates before entering the pug mill (see Figure 2.8) or directly into the pug mill. Here. the appropriate amount of new bitumen is added to the mixture according to desired end properties. It is important to avoid super heating of the added RAP. "Cold" methods imply recycling percentages of 10-40%, depending on the RAP moisture content the type of the plant’s vapor extraction system, the RAP quality in relation to the required specification the new hot mix and the technical process limitations regarding maximum permitted temperatures.

Employing the hot method means that the RAP is directly preheated (see Figure 2.9). This method relies on an extra dryer (tandem TM drum). The RAP is metered, heated and dried in the second drum and transferred via a buffer silo to the mixer. Virgin aggregates are superheated in the first drum and conveyed to the pug mill mixer in the “cold” method above. The hot gases from the recycling drum are either directed to the first drum as secondary air near the burner or to the baghouse. Recycling percentages for the hot method are typically 30-80%, the upper limit being determined by the quality requirements of the mix specification in relation to the properties of the old asphalt.

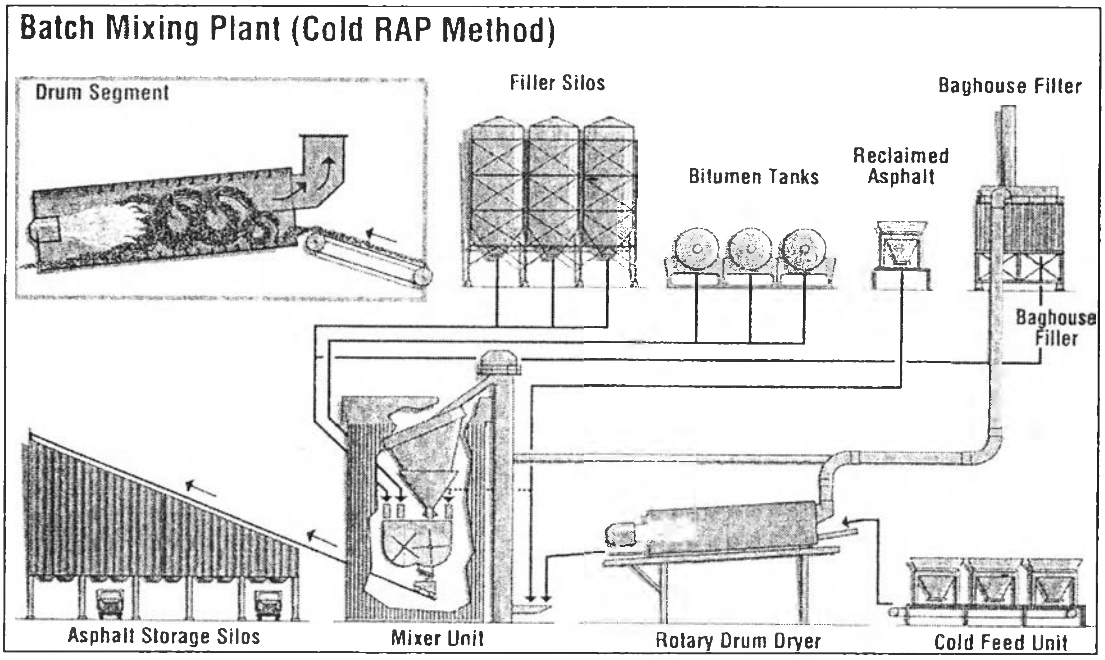


Figure 2.8 Batch mixing (cold) of RAP plant (Pedersen *et al.*, 2005).

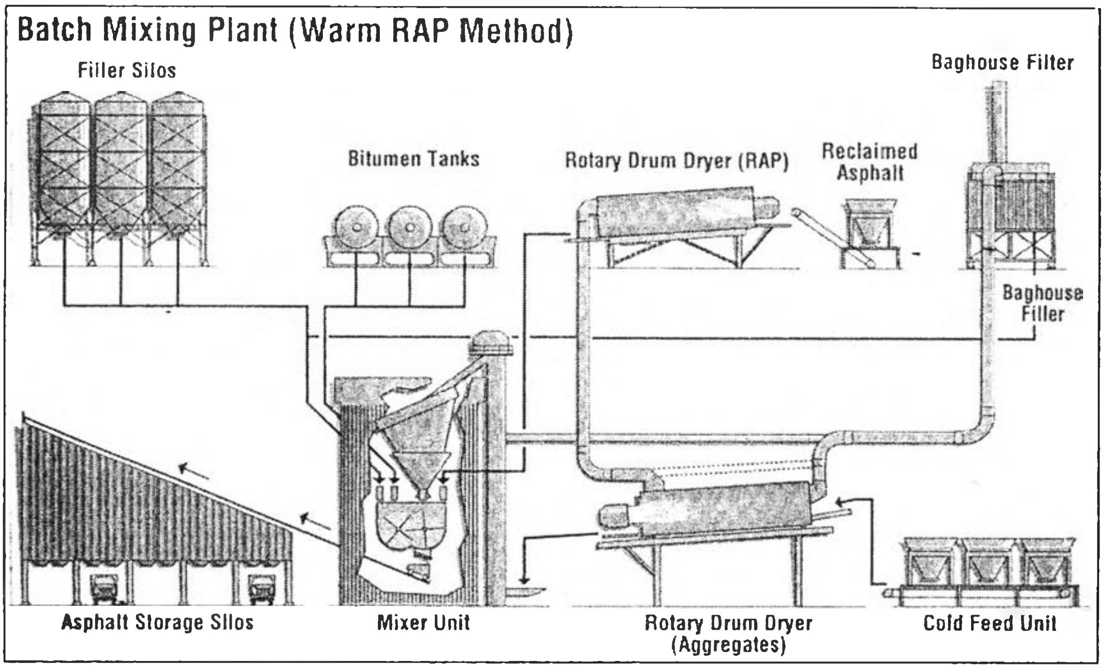


Figure 2.9 Batch mixing (hot) of RAP plant (Pedersen *et al.*, 2005).

For drum mix technology many recycling techniques have been developed throughout the years. This presentation mentions only the most successful ones. In a drum mixer, both the heating (and drying of aggregates) and the mixing (of aggregates, filler and bitumen) take place inside the drum. Basically it is possible to identify three different methods of heating recycled material before the bitumen is added: depending on the type of drum mixing: parallel follow, counter flow or Double Barrel™. The most common design for drum mixers today (parallel flow) use both the direct flame heating and superheated aggregate principles. In so-called split feed drum mixers the processed reclaimed asphalt is introduced at about the midpoint ("RAP ring") of the parallel flow drum (see Figure 2.10): both the superheated virgin aggregates and the hot burner gases heat the bituminous material.

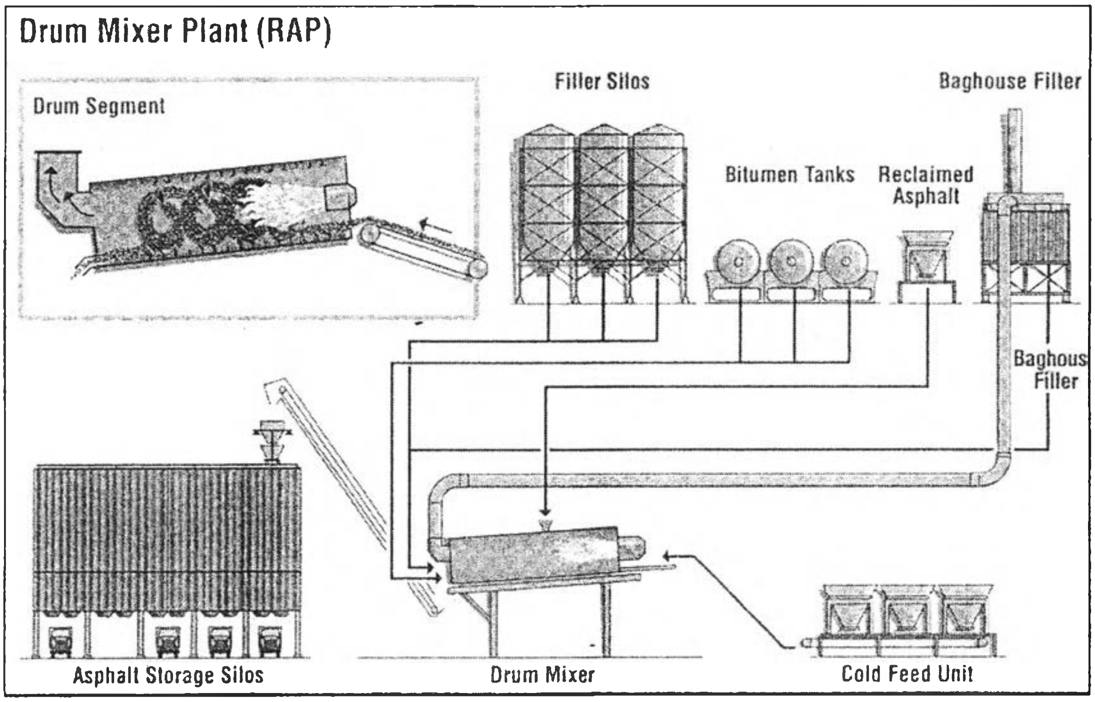


Figure 2.10 Drum mixing of RAP plant (Pedersen *et al.*, 2005).

The cold-mixed technology in a central plant is a recent development that had been successfully used for several years already. Reclaimed asphalt is returned to off-site plants with the same controlled crushing and screening process as for hot-mixed recycling. So as to produce a consistent feedstock the similar requirements of the feedstock for hot and cold mix plats make it feasible to operate both processes on the same location. Two types of binder, foamed bitumen and bitumen emulsion, have been used combined with the recycled asphalt in a pug-mill. The methods are both able to accommodate over 90% of recycled asphalt producing materials at a low energy cost with an appropriate design life. The final engineering properties may in some cases be inferior to that of hot mix, but in others cases when using end-product specifications can be at least equal. The smaller number of components and less complex nature of cold-mixed plants has led to their successful adoption when needed in remote locations for short-term reconstruction programs.

2.4.1.2 *In-Situ Recycling*

- Hot-mixed recycling
- Cold-mixed recycling

For hot-mixed in-situ recycling, the techniques are all similar in concept and require the use of special sets of equipment which have several brand or patent names, among them are Road train, Reshape, Repave and Remix (see Figure 2.11). The specialized nature of the plants and the size of economically viable contracts have widely limited their use widely throughout the European Union, however they are an important maintenance tool, where successfully established. They all involve the part removal or scarification of the existing pavement to a controlled depth: then they heat and mix the RAP, to which bitumen and/or virgin aggregates can be added, before laying back the reclaimed mixture. Among their advantages there is the reduction in RAP transportation to an off-site recycling facility and the rapid re-opening of a new road surface with improved riding qualities to traffic.

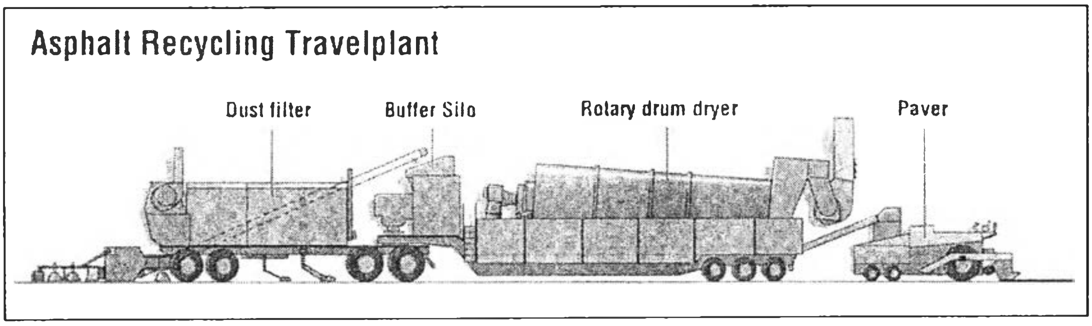


Figure 2.11 Hot-mixed in-situ tools (Pedersen *et al.*, 2005).

For cold-mixed in-situ recycling, the same two techniques that have been successfully adapted for off-site plant recycling were originally developed for in-situ recycling using specialized plants.

The bitumen emulsion based system involves the scarification bitumen emulsion mixing and compaction of RAP before overlay with a new wearing course. The foamed bitumen process requires the use of an improved milling machine, which pulverizes the existing pavement in a hood that also acts as a chamber in which the bitumen is foamed and mixing takes place. The recycled pavement is then spread ready for compaction and the application of a new running surface (Figure 2.12 and 2.13).

The processes both allow for the rapid reconstruction of existing pavement and a significant reduction in the quantity of material removal from the site for reprocessing elsewhere. Some current internationally coordinated research projects are aiming for further improvement of this technology. In some areas and particularly the Nordic countries, the oil gravel process is used to reconstruct in-situ pavements in remote locations where plants are not available either for hot-mixed production or cold-mixed recycling.

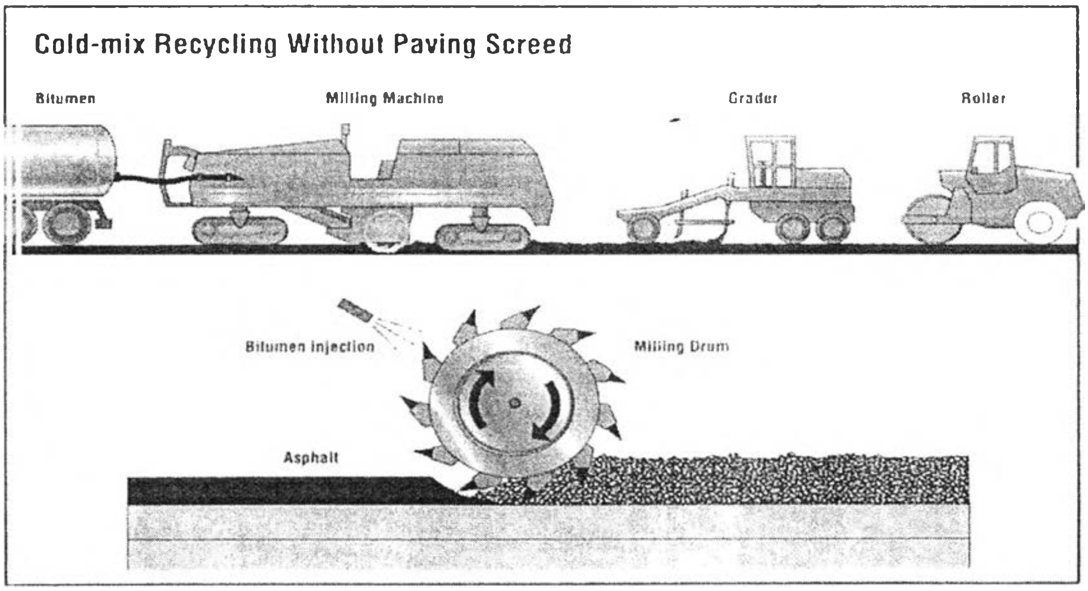


Figure 2.12 Cold-mixed in-situ tools (without paving screed) (Pedersen *et al.*, 2005).

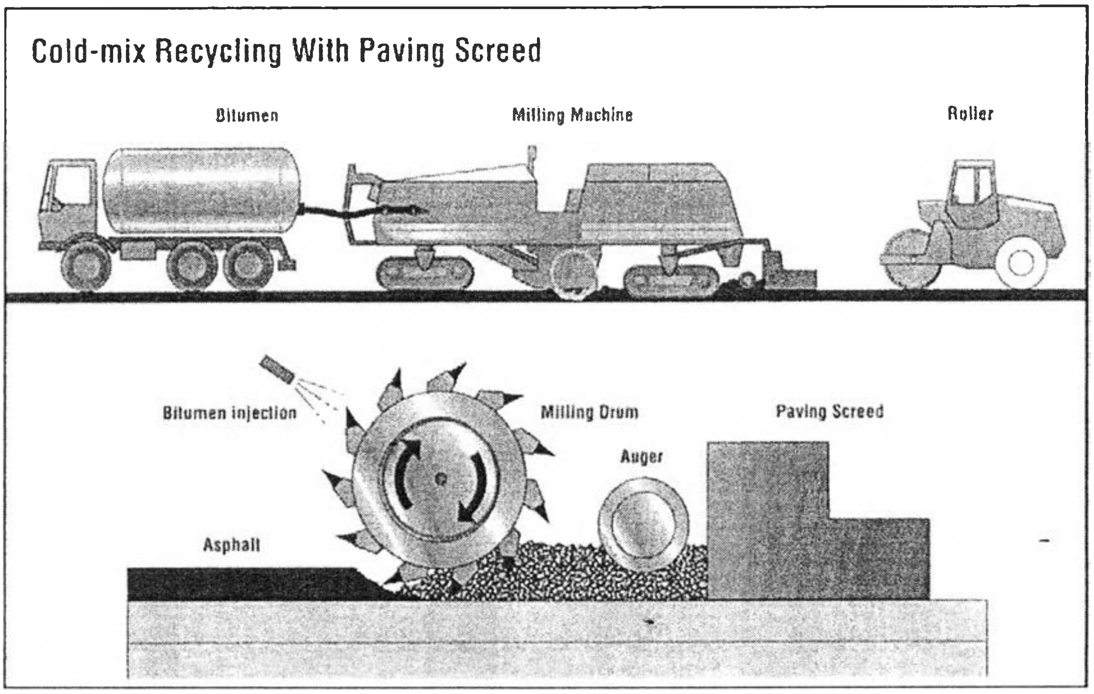


Figure 2.13 Cold-mixed in-situ tools (with paving screed) (Pedersen *et al.*, 2005).

2.4.2 Studies on RAP

Dinis-Almeida *et al.* (2012) studied the low temperature technique for pavement recycling in Portugal, which consists of the warm mix recycled asphalt (WMRA) with bitumen emulsion. It is considered a very interesting solution in terms of technical, economic and environmental performance. Stiffness and fatigue resistance was evaluated by four point bending test was carried on. Permanent deformation was determined by wheel tracking test. Different asphalt recycled mixtures having different bitumen emulsion content were tested. An economic study for application of such mixtures was also made. Their case study presented concerns a rehabilitation work of Portuguese National Road EN 244, between PonteSôr and the crossroad with EN 118. This rehabilitation work has a total length of 24,2Km. This road is part of a rural area but with some small urban areas temperature. The old pavement was removed to a depth of 7cm, corresponding to two different layers carried out in 1987, 6cm from the surface and 1cm from the base. The RAP was carried to a mix plant in truck dumpers. The RAP was homogenized before being introduced into the mix drum. The WMRA was produced in a hot mix continuous plant. It was necessary to do some adjustments to hot mix plant at level of the burners, since the work was done in lower temperatures than normal in the production of hot mix. Besides that, to control the mixture temperature was necessary to add some temperature sensors, in particular, at the exit of the dryer, in the elevator and at the entry and exit of the mixing drum. The mix composition (in percentage with respect to the aggregate weigh) applied in the National Road was the following (Soto, J.A *et al.*, 2008) 100% of RAP, 0% of added water and 2% of bitumen emulsion (RECIEMUL 90 - slow setting).

After mix production, it was moved out of the central plant directly to the trucks being carried to the site work. The mixture temperature at central plant was of 90 °C, approximately. The placement and the first compaction of the WMRA were obtained by a conventional asphalt paving machine allowing the obtaining of a uniform and smooth layer. The compaction was carried out at the temperature of 85 °C approximately, with a steel-wheel vibratory roller followed by a pneumatic-tire roller. The result showed that, Stiffness modulus and fatigue resistance results for the frequencies of 10 Hz of the WMRA with 100% RAP, 2, 0% and 1, 5% emulsion content are similar to those obtained in HMA. In the wheel tracking tests done at 60 °C it was concluded that the permanent deformations obtained are much higher than those recommended. However the tests done at 45 °C the mixtures present important improvements. The economic analysis concluded that taking into account the unavoidable milling of the old pavements and the cost that is associated to it, the benefit in the reuse of the RAP in the bituminous mixtures is clear.

Jamshidi *et al.* (2012) characterizes the effects of reclaimed asphalt pavement (RAP) source on the rheological properties of virgin asphalt binders blended with 15% and 30% recovered binders. The recovered binders were extracted from three local RAP sources namely; the North-South Expressway (NSE), Damansara-Puchong Expressway (DPE) and Public Works Department (PWD) roads. Environmental impacts were analyzed by estimating fuel requirements and Greenhouse Gas emissions in an asphalt mixing plant which was found to depend on RAP source and RAP content. From this project their found that RAP binder using Superpave^{TM} binder tests at high and intermediate temperatures as well as different aging states showed that RAP source and RAP content have significant effects on the asphalt binder properties. Changes in asphalt binder performance gradation also depended on RAP source and RAP content which the maximum asphalt upgrading was PG76 for 30D, while the maximum upgrading was PG70 using the identical amount of RAP from the other RAP sources. The maximum construction temperature was also for 30D. And for the assessment of preliminary fuel requirements and GHG emissions are benefit.

2.5 Life Cycle Assessment (LCA)

Now a day all the countries want to develop and achieve in theirs economic financial and social. And if they want to achieve more than other country, they must go to sustainable development. Especially for an industry, all of the processes and products are needed to achieve in sustainable development. So the achieving sustainable development requires methods and tools to quantify and compare the environmental impacts of each product. Every product has a life, starting with design or development of the product, followed by production and consumption, and finally end-of-life activities including collection, waste disposal, reuse, and recycling (Rebitzer *et al.*, 2004). All of the processes throughout the product's life result in the environmental impacts due to consumption of resources, generation of wastes, and emissions of substances. Figure 2.14 shows a simplified scheme of the product life concept which is usually referred to as a ''life cycle''.

2.5.1 History of LCA

Life cycle assessment (LCA) was developed around the late-1960s and early 1970s, a period in which oil crisis and environmental issue became a broadly public concern (Klopffer, 1997). It became obvious that the petroleum resource will last forever and the exponential economic growth might result in both environmental and social disaster. Therefore, the concept of energy and environmental analysis, which had been conducted for several years, was later broadened to encompass resource requirement, waste generation, and emission loading.

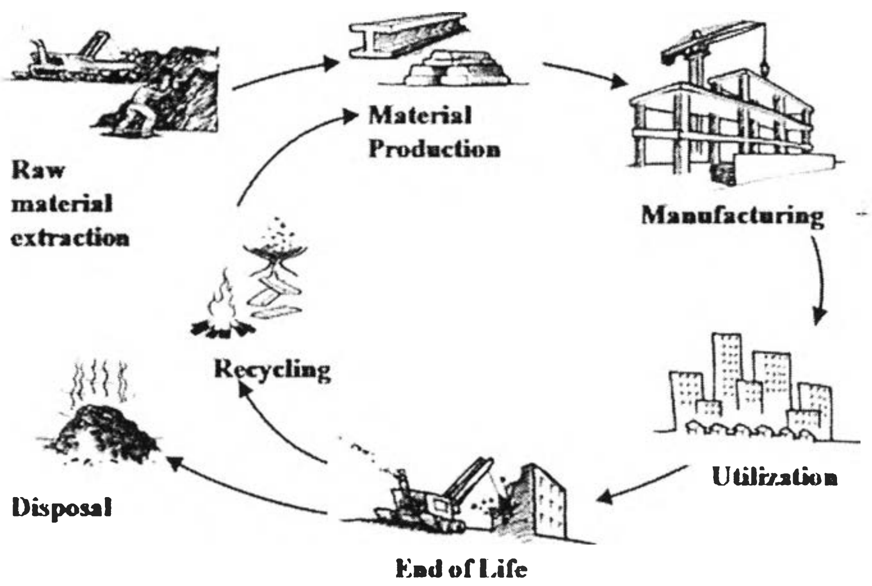


Figure 2.14 Schematic representation of a generic life cycle of a product (Rebitzer *et al.*, 2004).

2.5.1.1 Decades of Conception (1970-1990)

Decades of conception are the beginning period of LCA with widely diverging approaches, terminologies, and results. LCA was performed by using different methods and without a common theoretical framework in this period. In 1969, the first LCA study was conducted by Midwest Research Institute (MRI) in the United States for the Coca Cola Company about different beverage containers (Klopffer, 1997, GUINEE *et al.*, 2010) In Europe, early LCA-like work started soon afterwards in Germany, England, Switzerland, and Sweden (Klopffer, 1997). The main topic was the comparative analysis of packaging under environmental aspects, especially with regard to resource conservation and energy saving. The Swiss Federal Laboratories for Materials Testing and Research (EMPA) published a report that presented a comprehensive list of the data needed for LCA study in 1984 (GUINEE *et al.*, 2010). In the late 1980s, not only packaging, but also many other systems were gradually studied and analyzed from "cradle to grave" (Klopffer, 1997, GUINEE *et* *al.*, 2010). Then a shift can be observed from comparative studies toward system optimization and benchmarking. It has been recognized that a large share of the environmental impacts of many products is not in the utilization of the product, but in its production, transportation, and disposal process.

2.5.1.2 Decade of Standardization (1990-2000)

The number of LCA research works and handbooks has been produced since the beginning of the 1990s (Russell *et al.*, 2005, GUINEE *et al.*, 2010). Many scientific journal papers have also been published. In the early 1990s, through its North Ameriean and European branches, the Society of Environmental Toxicology and Chemistry (SETAC) shaped the development of LCA in a series of important workshop resulting in the "Code of Practice" in 1993 (Perriman, 1993, Ekvall, 2005). This document describes a procedural framework for LCA and also includes some methodological recommendations. Next to SETAC, the International Organization of Standardization (ISO) has been involved in LCA since 1994 in order to start a standardizing process (Arvanitoyannis, 2008). Therefore, this period can be characterized as a period of convergence between SETAC's coordination and ISO's standardizing activity.

Nowadays, LCA becomes increasingly important due to awareness of the environmental impacts caused by products. Governments and corporations all over the world also encouraged the use of LCA (Reap *et al.*, 2008). As a result, LCA has become a core element in environmental policy as well as voluntary action.

2.5.2 Definition of LCA

Two of the most widely accepted definitions of LCA are presented below as they have been chronologically formulated to date. Below is the definition of LCA by ISO 14040.

"LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by following.

1) Compiling an inventory of relevant inputs and outputs of a product system.
2) Evaluating the potential environmental impacts associated with those inputs and outputs.

3) Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

LCA studies the environmental aspects and potential impacts throughout the product's life (i.e. cradle to grave) from raw materials acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences".

2.5.3 LCA Methodology

According to ISO 14040, improvement assessment is no longer regarded as a phase on its own, but rather as having an influence throughout the whole LCA methodology (Rebitzer *et al.*, 2004). Moreover, interpretation which is a phase that interacts with all other phases in the LCA has been introduced as illustrated in Figure 2.15 below. In practice, an LCA is often conducted iteratively, repeating some of the phases several times in order to eliminate uncertainties (Widheden *et al.*, 2007).

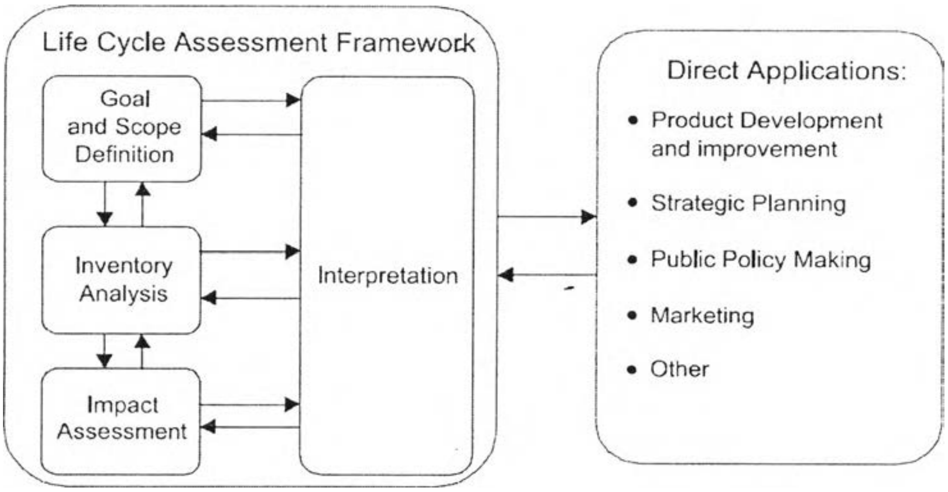


Figure 2.15 General methodological framework of LCA.

2.5.3.1 Goal and Scope Definition

The goal and scope definition phase in the LCA is the planning phase which attempts to set the extent of the inquiry and provides the following descriptions of the product system (Widheden *et al.*, 2007):

- Objectives

The ISO 14040 standard states that the goal definition "shall unambiguously state the intended application, the reason for carrying out the study and the intended audience".

- System boundaries

The scope defines the boundaries of the study, including the products and unit processes for which data are to be collected, and the geographical locations and technological levels of these processes, resulting in a strategy for data collection.

- Functional unit

The functional unit, which is the basis for the calculation, is a measure of the performance that the system delivers and also enables alternative products to be compared and analyzed.

- Assumptions and limitations

The assumptions and limitations are very important to each LCA in case of the internal consistency of the study.

- Allocation methods

The allocation methods are used to partition the environmental load of a process when several products or functions share the same process.

- Impact categories

The impact categories represent environmental issues of concerned, which LCI results may be assigned. The impact catagories which are selected in each LCA study have to be able to describe the impacts caused by the products being considered or the product system being analyzed.

2.5.3.2 Inventory Analysis

Life cycle inventory (LCI) is a methodology for quantifying the flow of material and energy attributable to a product's life (Rebitzer *et al.*, 2004, Reap *et al.*, 2008). The implication of the inventory analysis is that all activities related to the production of one functional unit have to be analyzed concerning about raw material, intermediate, product, usage, and waste removal (Klopffer, 1997). An LCI analysis includes (Widheden *et al.*, 2007) following.

- Construction of a flowchart representing the product system according to the system boundaries decided in the goal and scope definition.
    - All material flows are traced from the extraction of raw materials to their release into the environment.
    - All transport operations are also included.
- Data collection for all activities in the product system, followed by data quality assessment and documentation of the collected data. Both numerical and qualitative/descriptive data need to be collected. The numerical data includes following.
    - Inputs: raw materials, auxiliary inputs and other physical inputs
    - Outputs: products and co-products
    - Emissions to air and water and waste

    The qualitative/descriptive data includes following.
    - Descriptions of the technology of the process
    - How and when emissions were measured and their uncertainty
    - The geographical location of the process/activity
    - Where inflows come from and outflows go to
- Calculation of the environmental loads of the system in relation to the functional unit.
    - The numerical data for the activities have to be recalculated to fit the functional unit and summarized into a list of parameters representing the entire life cycle of the product.
    - The result of the inventory analysis is the inventory table which is a list of all inputs and outputs per functional unit.

2.5.3.3 Impact Assessment

Since life cycle inventory (LCI) provides hundreds of parameters, it is difficult to draw any conclusions from LCI. Therefore, a formal impact assessment has to be performed. Life cycle impact assessment (LCIA) provides indicators and the basis for analyzing the potential contributions of the resource consumptions, waste generations, and emissions in an inventory analysis to a number of potential impacts (Rebitzer *et al.*, 2004). The result of the LCIA is an evaluation of a product life cycle, on a functional unit basis, in terms of several impact categories. According to the ISO 14040 standard for LCIA, the following steps have to be performed in order to convert the inventory data into the environmental impact (Klopffer, 1997; Widheden *et al.*, 2007; Reap *et al.*, 2008).

- Impact category definition

Some baseline examples of impact category considered in most of the LCA studies are illustrated in Table 2.4.

- Classification

Assignment of LCI result parameters to their respective impact categories, e.g., classifying CO_2 emission to global warming.

- Characterization

Modeling LCI impacts within impact categories using science-based conversion factors, e.g., modeling the potential impact of CO_2 and methane on global warming.

- Normalization

Relating the characterization results to a reference value in order to be compared, e.g. relating the impacts of the studied product to the impacts of the total amount of pollutants emitted in a region.

- Grouping

Sorting and possibly ranking of the indicators, e.g. sorting according to global, regional or local impact or sorting according to high, medium or low priority.

- Weighting

Aggregation of characterization results across impact categories into one total environmental impact value in order to generate a single score and also emphasizing the most important potential impact.

2.5.3.4 Interpretation

Life cycle interpretation, which occurs at every stage in an LCA, is a process of assessing results in order to draw conclusions. It is a critical evaluation of the whole LCA using mathematical tool such as sensitivity analysis and dominance analysis (Klopffer, 1997). For example, if two product alternatives are compared and one alternative shows higher consumption of resource and emission of CO_2, an interpretation purely based on the LCI and LCIA data can be conclusive. In other word, the interpretation phase is desirable to prioritize areas of concern within a single life cycle study (Rebitzer *et al.*, 2004). Moreover, it also links the LCA with the applications which are not part of LCA. The International Organization for Standardization (ISO) has defined the following two objectives of life cycle (Klopffer, 1997; Widheden *et al.*, 2007; Reap *et al.*, 2008) following.

- Analyze results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA and then report the results of the life cycle interpretation in a transparent manner.
- Provide a readily understandable, complete, and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study.

The interpretation should include following.

- Identification of significant issues based on the results of the LCI and LCIA of an LCA.
- Evaluation of the study considering completeness, sensitivity and consistency checking.
- Conclusions, limitations and recommendations.

2.5.4 Application of LCA

As mentioned, LCA is a method to help quantify and evaluate the potential environmental impacts of products. This implies that LCA can be applied to any applications where the environmental impacts of the complete or part of the product's life cycle are of interest. For instance, LCA can be used in order to identify significant environmental aspects and also provide a baseline for decisions about product improvements in product development projects.

Table 2.4 Baseline examples of impact category (Iuga, 6 April 2009)

Impact category	Category indicator	Characterization model	Characterization factor
Abiotic depletion	Ultimate reserve, annual use	Guinee and Heijungs 95	ADP[9]
Climate change	Infrared radiative forcing	IPCC model[3]	GWP[10]
Stratospheric ozone depletion	Stratospheric ozone breakdown	WMO model[4]	ODP[11]
Human toxicity	PDI/ADI[1]	Multimedia model, e.g. EUSES[5], CalTox	HTP[12]
Ecotoxicity (aquatic, terrestrial, etc)	PEC/PNEC[2]	Multimedia model, e.g. EUSES, CalTox	AETP[13], TETP[14], etc
Photo-oxidant formation	Tropospheric ozone formation	UNECE[6] Trajectory model	POCP[15]
Acidification	Deposition critical load	RAINS[7]	AP[16]
Eutrophication	Nutrient enrichment	CARMEN[8]	EP[17]

[1] PDI/ADI Predicted daily intake/Aceptable daily intake

[2] PEC/PNEC Predicted environmental concentrations/Predicted no-effects concentrations

[3] IPCC Intergovernmental Panel on Climate Change

[4] WMO World Meteorological Organization

[5] EUSES European Union System for the Evaluation of Substances

[6] UNECE United Nations Economic Commission For Europe

[7] RAINS Regional Acidification Information and Simulation

[8] CARMEN Cause Effect Relation Model to Support Environmental Negotiations

[9] ADP Abiotic depletion potential

[10] GWP Global warming potential

[11] ODP Ozone depletion potential

[12] HTP Human toxicity potential

[13] AETP Aquatic ecotoxicity potential

[14] TETP Terrestrial ecotoxicity potential

[15] POCP Photochemical ozone creation potential

[16] AP Acidification potential

[17] EP Eutrophication potential

Governmental organizations, non-governmental organizations, and industries have applied LCA in a wide variety of sectors, either autonomously or with the help of research institutes or consultants (Rebitzer *et al.*, 2004). For example, LCA can be used for identifying and improving waste treatment strategy in the nation level. Another application area is marketing. The LCA results can be used to communicate the environmental benefits of a product to customers, e.g., through the LCA-based communication tool environmental product declaration (EPD) (Widheden *et al.*, 2007).

While noting a great importance of LCA in many applications, activities in various industrial sectors and changes in consumer behavior are ultimately the most crucial factors for reducing the environmental impacts associated with products.

2.5.5 LCA Studies of Asphalt

2.5.5.1 LCA Study from Previous Study

From phase one study, a cradle-to-gate life cycle assessment (LCA) technique based on ISO 14040 series is performed to evaluate hot-mixed asphalt (HMA) and warm-mixed asphalt (WMA) in terms of energy and environmental impact. The main focus is to compare WMA (conventional asphalt with additive "Sasobit") and conventional hot-mixed asphalt production and pavement (see Figure 2.16) in order to identify benefits in both energy aspect and greenhouse gases (GHG) reduction. The system boundary includes provision of asphalt, raw materials auqisition. asphalt production, paving, and all transportations based on functional units of 1 ton of asphalt product and 1 km x 7 m x 0.05 m road pavement. For HMA, relevant data are collected at actual production sites of Thaiwat Engineering Co., Ltd (Bangbuatong), including pavement. However, for WMA, since we cannot gain acceptance the actual warm-mixed asphalt data from Thaiwat Engineering Co., Ltd (Sriracha) at the time of this study, both production and pavement data for LCA analysis are estimated from HMA based on similar research study in the literature. The results of HMA and WMA are compared together based on functional units and also with those of other studies. The following points can be summarized as the conclusions of this study: the global warming potential (GWP), represented by GHG emissions, comes mostly from raw material and asphalt production with little contribution from transportation and pavement process. The results show that WMA provides considerable environmental benefits compared to HMA in both energy and GHG reduction aspects (see Figure 2.17 and 2.18). This is mainly contributed to the decrease in mixing temperature from 160 to 140°C and also pavement temperature. Consequently, the results showed that WMA had better performance in both GWP and energy aspects, but the benefits were not significant (<5%). More environmental benefits can be expected if the mixing temperature is further decreased. In comparison to other studies, the energy and environmental performance of HMA and WMA in Thailand is not as good as those observed in other countries, which is speculated to be due to lower efficiency in the asphalt production and high uncertainty of the data obtained from actual production plant. Finally, the end of life phase has shown to be important in improving the life cycle performance of asphalt. It is obvious that recycling process helps reduce both energy input and GWP impact such that the more recycle leads to the better environment performance of asphalt.

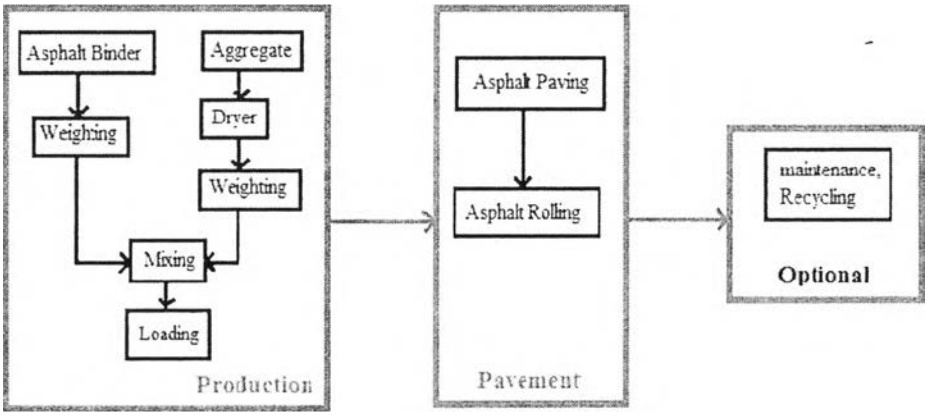


Figure 2.16 System boundary of the LCA warm-mixed asphalt from previous study.

2.5.5.2 Other LCA Studies on Asphalt

Huang *et al.* (2009) reviewed relevant LCA resources worldwide (Figure 2.19), identified the knowledge gap for the road industry, and described the development of an LCA model for pavement construction and maintenance that accommodates recycling and up-to-date research findings. Details are provided of both the methodology and data acquisition. In this study their have the case study, which study the model is applied to an asphalt paving project at London Heathrow Terminal-5 (LHR), in which natural aggregates were replaced with waste glass, incinerator bottom ash (IBA) and recycled asphalt pavements (RAP). Production of hot mix asphalt and bitumen was found to represent the energy intensive processes. This is followed by data analysis and sensitivity check. Further development of the model includes expanding the database to accommodate the recycling and maintenance practice in the UK, and taking into account the effect that roadwork has on traffic emissions. The LCA model can be further tested and calibrated as a decision support tool for sustainable construction in the road industry.

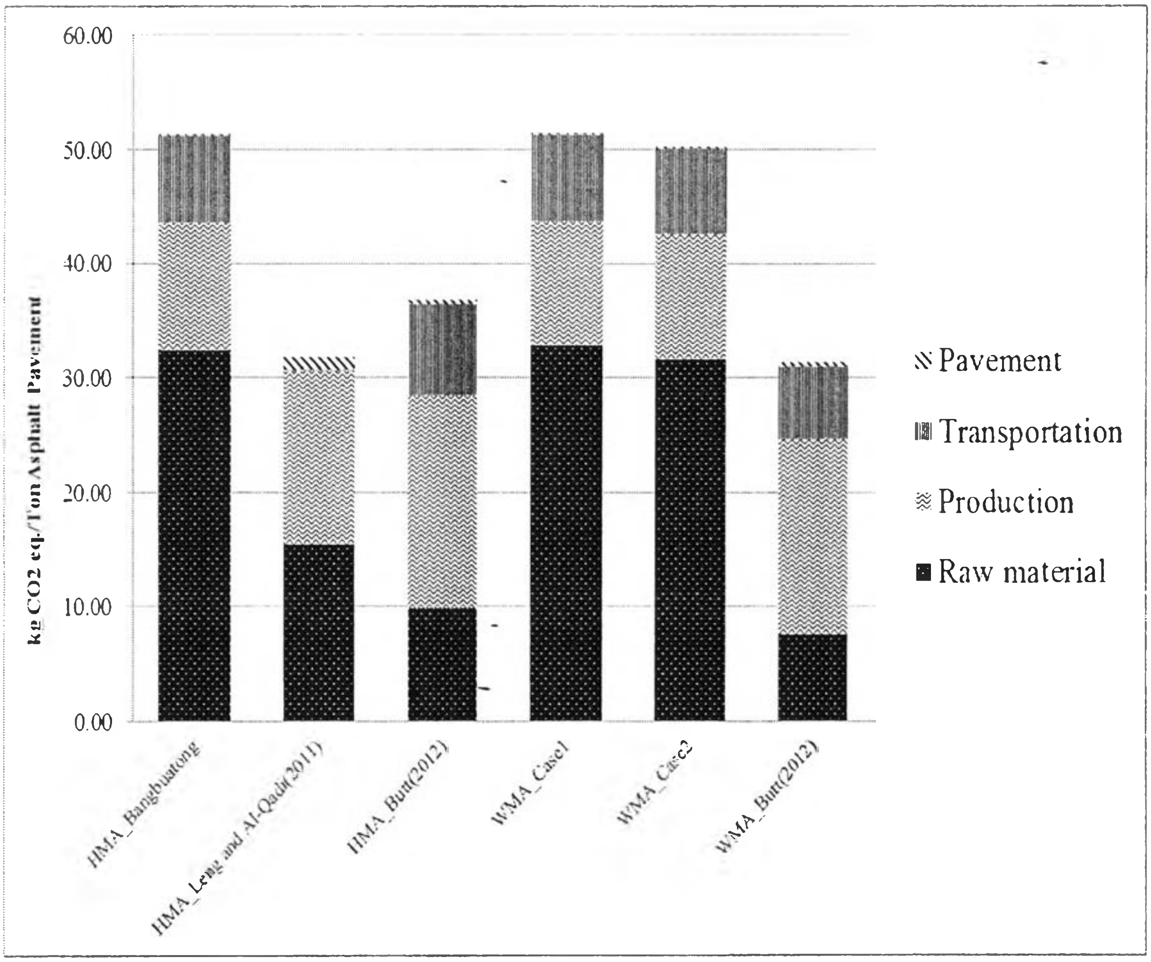


Figure 2.17 Comparison of GWP between HMA from Bangbuatong plant, WMA from calculation and other studies by CML 2 baseline 2000.

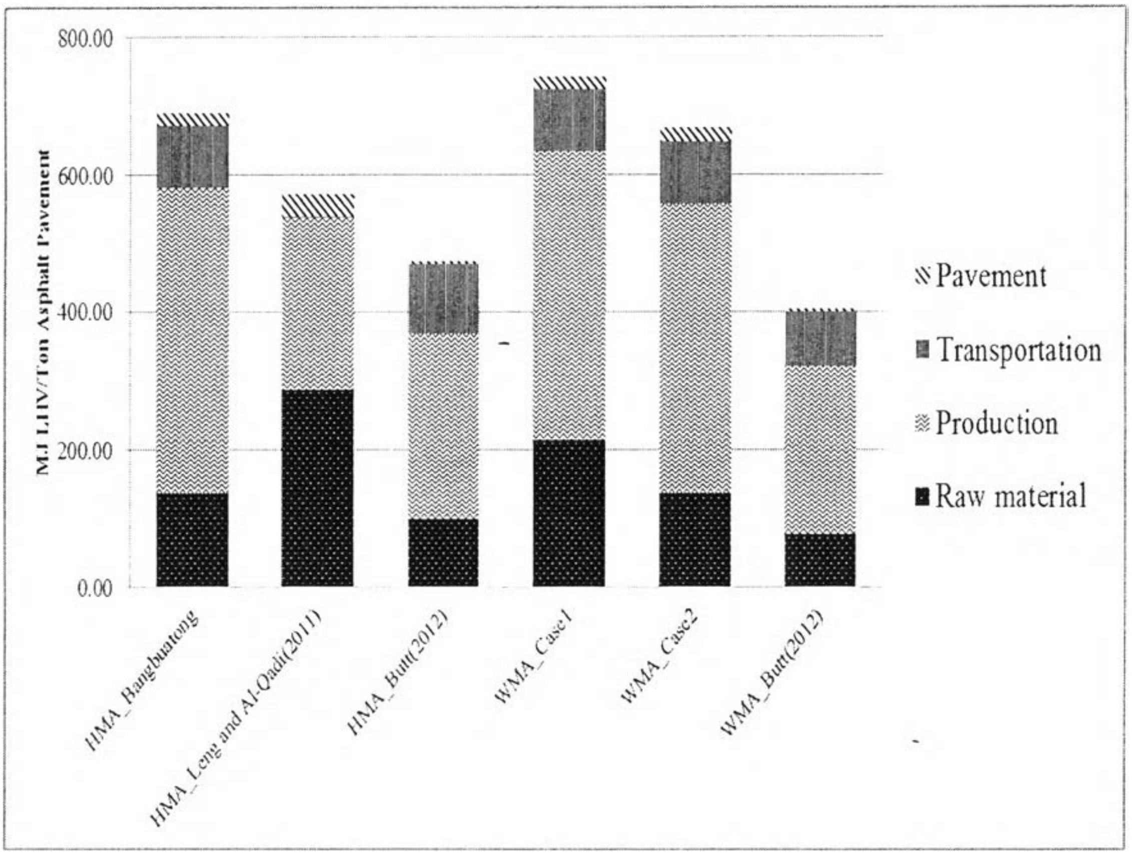


Figure 2.18 Comparison of energy resource between HMA from bangbuatong plant, WMA from calculation and other studies by using Eco-Indicator 95 method.

Chowdhury *et al.* (2010) studied a comparison of these by-products such as coal fly ash, coal bottom ash, and recycled concrete pavement (RCP) with natural aggregates was carried out with respect to cost, environmental pollutants generated, and energy consumption (Figure 2.20). Pollutant emission data were aggregated to express results in terms of global warming potential (GWP), acidification potential and various toxicity potentials. In general, mixed results were found from the LCA and no single material performed superiorly in all categories (Figure 2.21). Fly ash and bottom ash were found attractive in cost, GWP, and acidification potential categories. However, if the transportation distance ratio of fly ash and bottom ash to natural aggregate is more that 1:3, fly ash and bottom ash have higher impacts on energy, GWP and AP categories. RCP has higher GWP and acidification potential compared to natural aggregates. However, if the transportation distance ratio of RCP: natural aggregate was more that 1:4, RCP was found attractive in energy, GWP and all the toxicity categories.

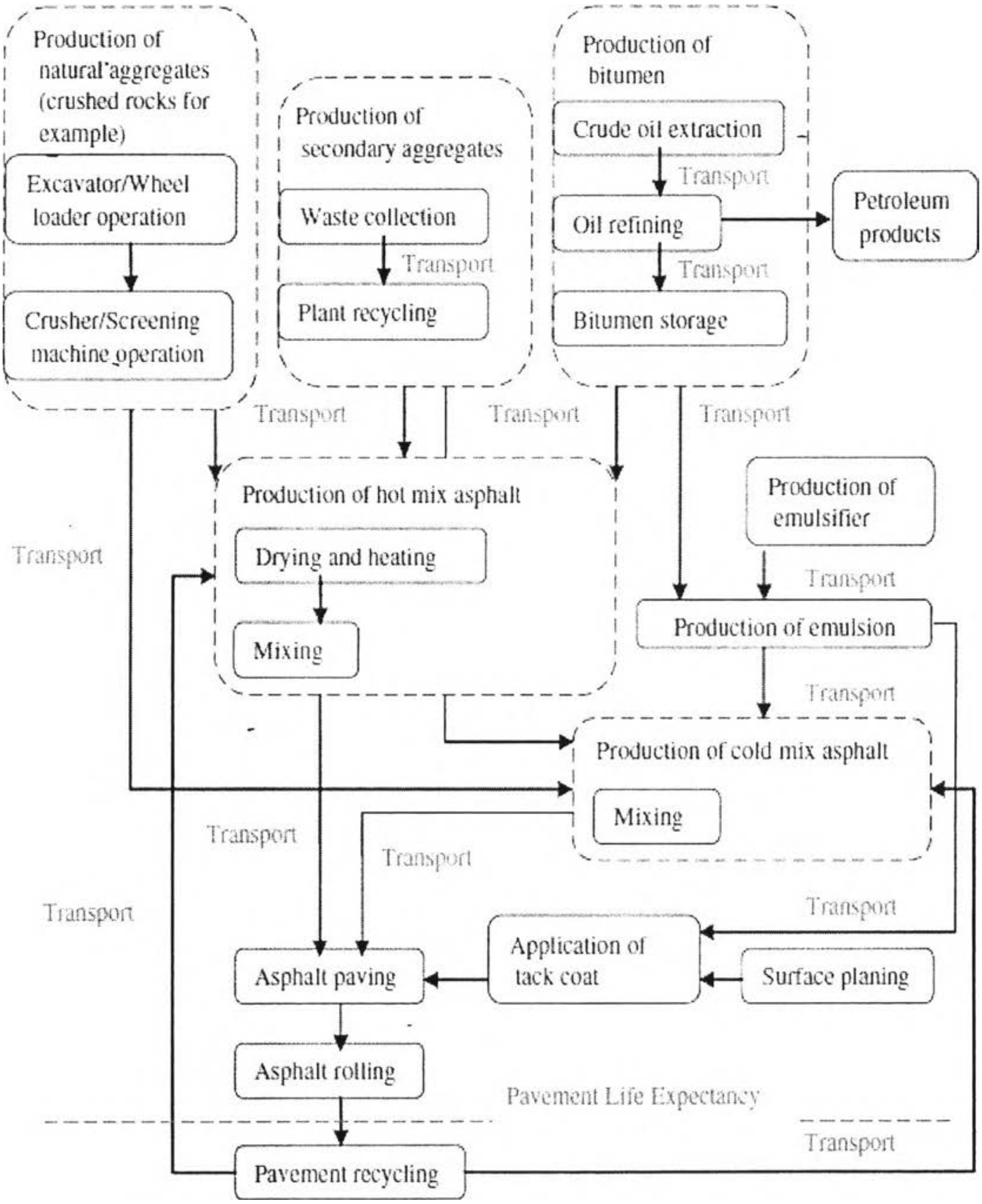


Figure 2.19 Life cycle process in asphalt pavement construction (Huang *et al.*, 2009).

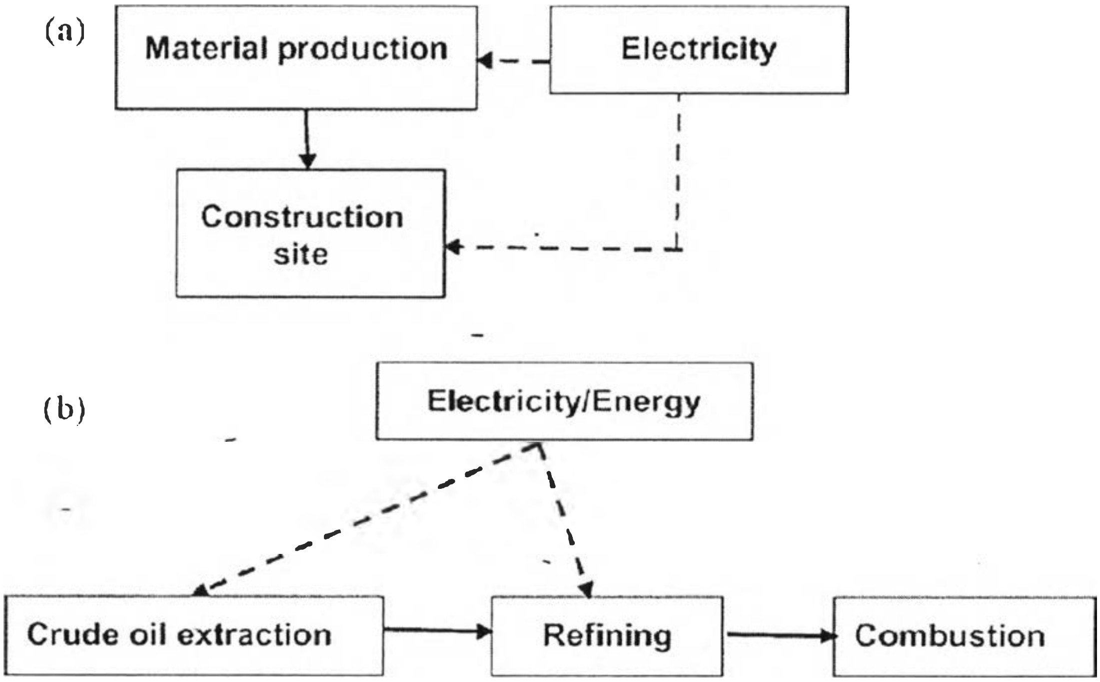


Figure 2.20 A schematic representation of the system boundary in the present study. (a) System boundary for a material production and (b) system boundary for the transportation (Chowdhury *et al.*, 2010).

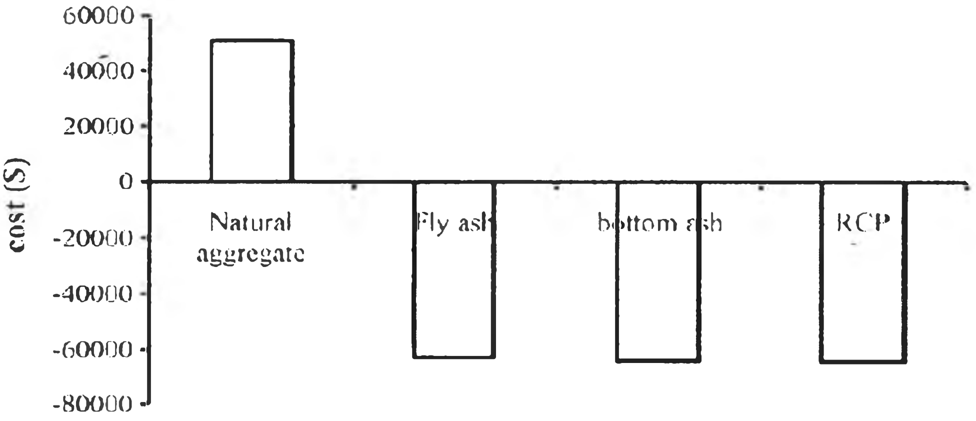


Figure 2.21 Cost of embankment construction using different materials (Chowdhury *et al.*, 2010).

Hassan (2010) was to conduct a lifecycle assessment of WMA technology as compared with a conventional hot-mix asphalt mixture (see system boundary in Figure 2.22). To achieve this objective, a life-cycle inventory (LCI) that quantifies the energy, material inputs, and emission during aggregate extraction, asphalt binder production, and hot-mix asphalt production and placement, was developed. Based on this inventory, life-cycle impact assessment of WMA technology was conducted. The result showed that (see Figure 2.23), in the use of WMA affects three main environmental factors: air pollution, fossil fuel depletion and smog formation WMA provides a reduction of 24% on the air pollution impact of HMA and a reduction of 18% on fossil fuel consumption. It also reduces smog formation by 10%. The use of WMA is estimated to provide a reduction of 15% on the environment impacts of HMA. Assuming a weight of 50% for economic factors and 50% for environmental factors, the overall performance score of HMA was 52.0 as compared to 48.0 for WMA.

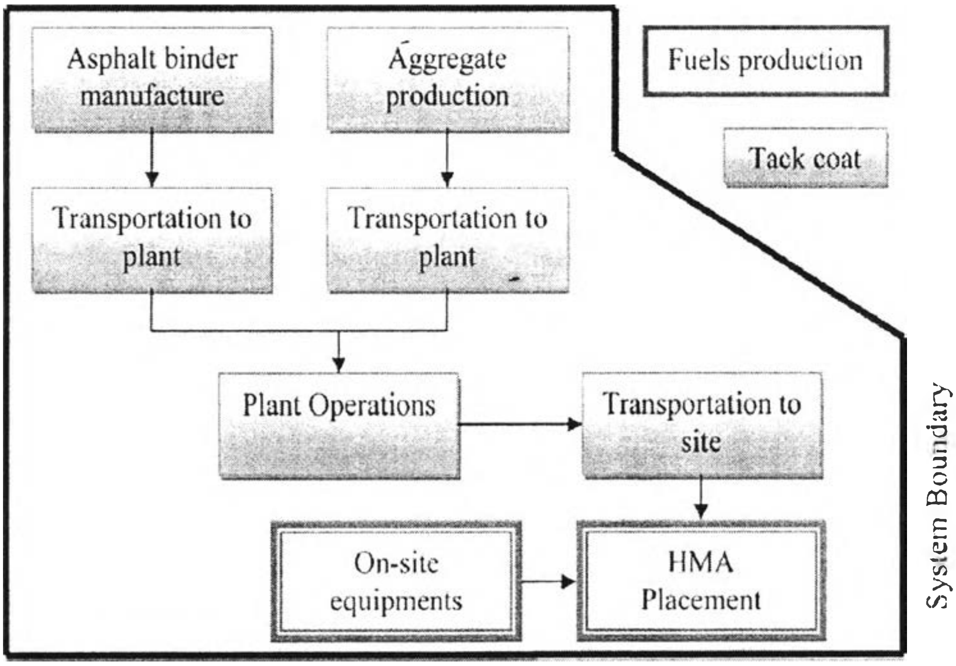


Figure 2.22 Hot-mixed asphalt system boundary (Hassan, 2010).

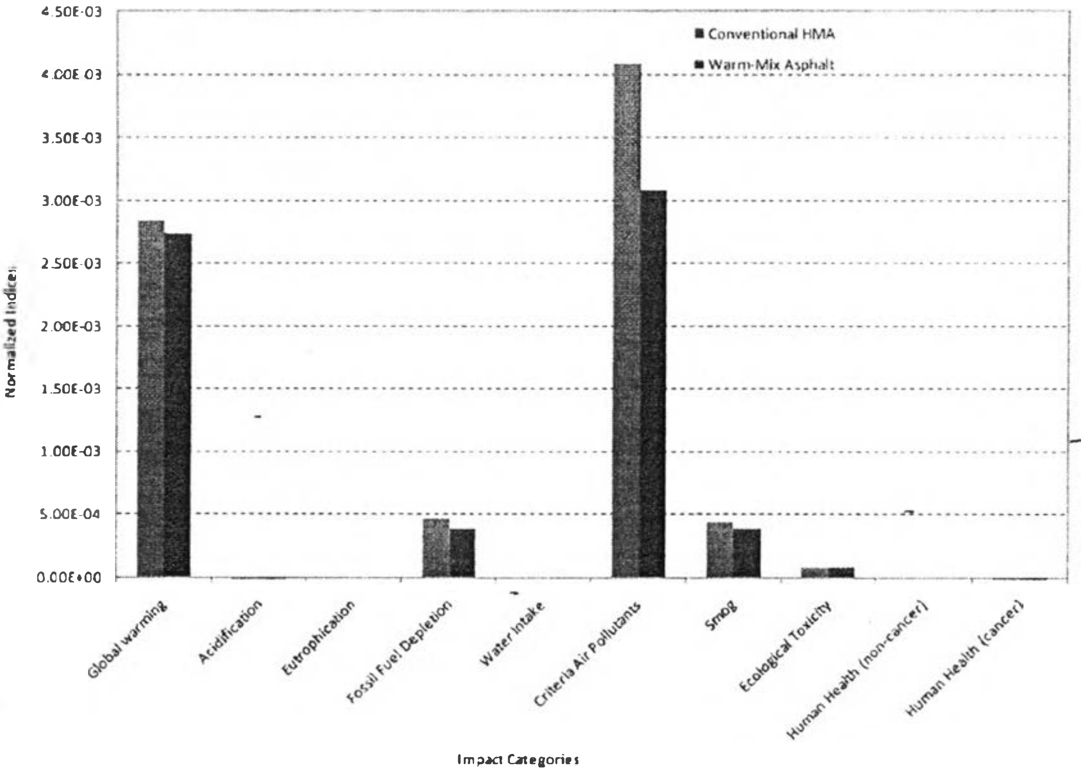


Figure 2.23 Environmental impacts of hot-mixed asphalt and warm-mixed asphalt (Hassan, 2010).

Tatari *et al.* (2012) developed a thermodynamic based hybrid life cycle assessment model to evaluate the environmental impacts of different types of WMA pavements and compare it to that of a conventional hot mix asphalt (HMA) one. The impacts on the ecosystem were calculated in terms of cumulative mass, energy, industrial energy, and ecological energy. Monte Carlo simulation was also conducted to analyze the variability of critical input parameters. The results of this study showed that although the mixing phase is important, it should not be the only phase to evaluate the amount of atmospheric emissions of asphalt pavements. The supply chain, which includes material production and transportation, is critical for a more comprehensive evaluation. In addition, enlarging the system boundary to include the whole ecological system revealed that WMA pavement sections consumed higher amounts of ecological resources when compared to the HMA control section (see Figure 2.24). Also, the differences in thickness of the asphalt layer played an important role in the analysis. Although economy wide comprehensive hybrid LCA tool is developed in the current study, there are still certain limitations and uncertainties due to the use of aggregate data for product assessment. Future studies should evaluate other WMA technologies such as the foamed WMA.

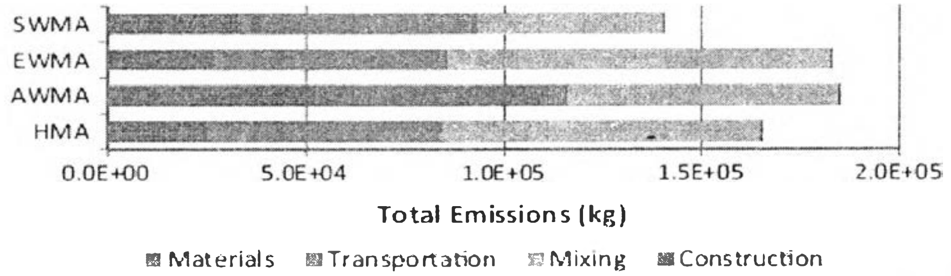


Figure 2.24 Total emissions by life cycle phase (kg) (Tatari *et al.*, 2012).

Kucukvar *et al.* (2012) recently evaluated the resource consumption and atmospheric emissions of continuously reinforced concrete and a hot mix asphalt pavements. The results suggested that the former is a better pavement design when total ecological resource consumption is considered but HMA is more sustainable in terms of energy and industrial energy utilization. Cement manufacturing is found to be the dominant phase for energy consumption of CRCP design with an associated large amount CO_2 being emitted. A Monte Carlo simulation looking at the variability in energy consumption and air emissions of CRCP with changing rate of fly ash suggests that replacing cement with fly ash shows a high sensitivity regarding energy consumption and atmospheric emissions (see Figure 2.25). Energy consumption is found to be higher for CRCP suggesting the higher fly ash content could decrease the energy consumption in CRCP.

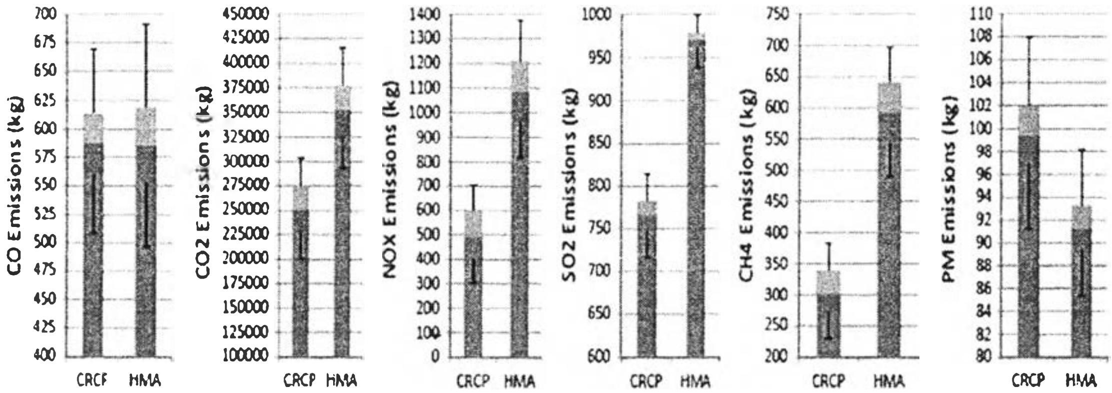


Figure 2.25 Life cycle emission differences (Kucukvar *et al.*, 2012).

2.5.6 LCA Studies of Reclaim Asphalt Pavement

Chiu *et al.* (2008) performed life cycle inventory using proposed recycled material formulas and service records and incorporating the database provided by Eco-indicator 99 in order to study the eco-burden presented by using recycled materials to rehabilitate asphalt pavements (see system boundary in Figure 2.26). Three recycled materials (recycled hot mix asphalt, asphalt rubber, and Glassphalt) and the traditional hot-mixed asphalt are compared. . The results show that (see Figure 2.27), when using traditional hot mix asphalt to rehabilitate asphalt pavement, the material and energy required is equivalent to an eco-burden of 3.45 kPt. per lane-kilometer. Using recycled hot mix asphalt can reduce the eco-burden by 23%. Using asphalt rubber will increase the eco-burden by 16%. The eco-burden remains essentially the same (less than 1% lower) using glassphalt instead. An analysis on the contribution from various sources during rehabilitation indicates that the majority of eco-burden comes from two sources, the asphalt and the heat required, no matter which material is used. The percentage is 39–48% for the asphalt and 42–50% for energy. Both are much higher than the percentages for sand, stone, electricity, and transportation. This suggests that the most effective way to lower the eco-burden may be to reduce the heat requirement during the manufacturing process.

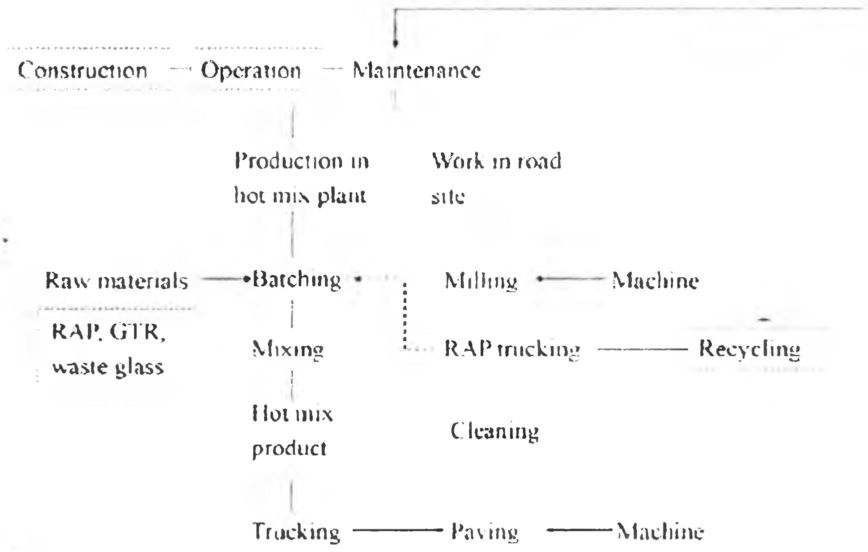


Figure 2.26 Life cycle of pavement maintenance investigated in this paper (Chiu *et al.*, 2008).

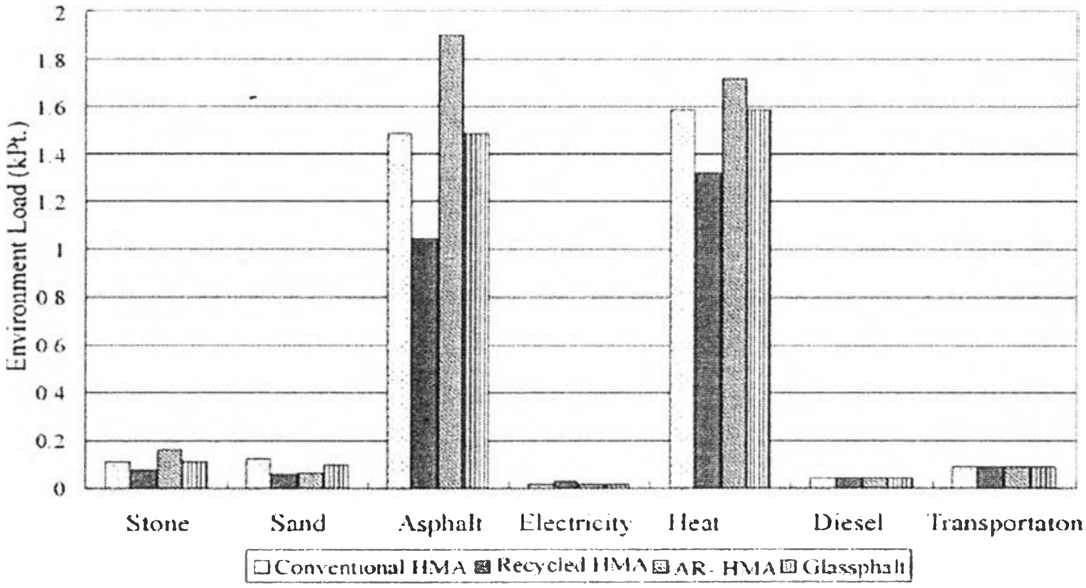


Figure 2.27 Environmental loads of milling/overlaying one lane-kilometer of asphalt pavement using different materials (Chiu *et al.*, 2008).

Vidal *et al.* (2013) studied the life cycle assessment of asphalt pavements including hot-mixed asphalt (HMA), warm-mixed asphalt (WMA) with the addition of synthetic zeolites, and asphalt mixes with reclaimed asphalt pavement (RAP) as showed in system boundary Figure 2.28. The environmental impacts associated with energy consumption and air emissions were assessed, as well as other environmental impacts resulting from the extraction and processing of minerals, binders and chemical additives; asphalt production; transportation of materials; asphalt paving; road traffic on the pavement; land use; dismantling of the pavement at the end-of-life and its landfill disposal or recycling. Four different asphalt pavements were assessed and compared for a particular road by using the LCA-based tool. The pavements evaluated include: HMA with 0% of RAP, HMA with 15% of RAP, zeolite-based WMA with 0% of RAP, and zeolite-based WMA with 15% of RAP. By comparing HMA and zeolite-based WMA throughout their entire life cycle, it was found that the impacts of WMA are almost equal to the impacts of HMA with the same RAP content. The reduction in the impacts of WMA due to lowering the manufacturing temperature is offset by the greater impacts of the materials used, especially the impacts of the synthetic zeolites. Moreover, by comparing the same type of asphalt mixes with different RAP contents, it was shown that the impacts of asphalt mixes are significantly reduced when RAP is added (see Figure 2.29). The use of RAP as a raw material avoids the need to extract a portion of the virgin raw materials, the need to process a portion of the bitumen, and the need to dispose of the asphalt to landfill. Thus, both the impacts of the materials and the impacts of the end-of-life are decreased. All endpoint impacts as well as climate change, fossil depletion and total cumulative energy demand were decreased by 13–14% by adding 15% RAP (Figure 2.30). A key advantage of WMA is the potentially greater use of RAP. Thus, the decrease in the impacts achieved by adding large amounts of RAP in WMA could turn these asphalt mixes into a good alternative to HMA in environmental terms.

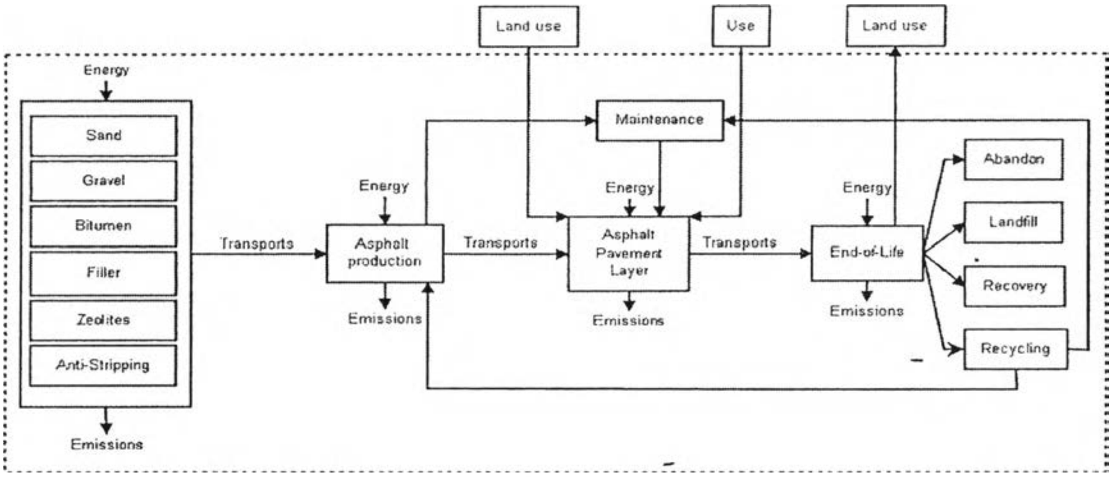


Figure 2.28 System boundaries of this paper (Vidal *et al.*, 2013).

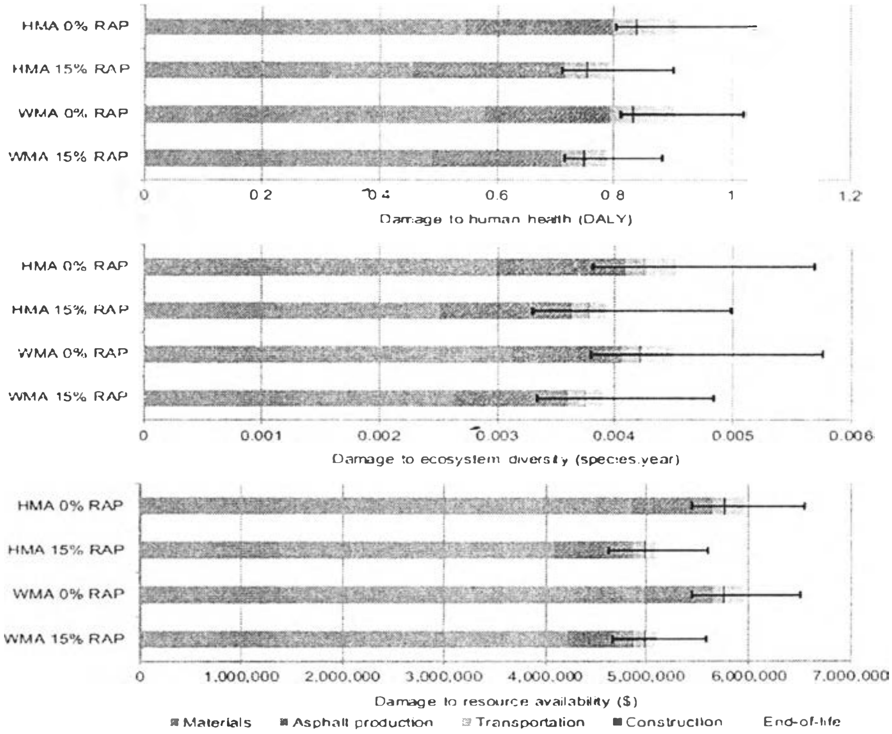


Figure 2.29 Damages to human health, ecosystem diversity, and resource availability of asphalt pavements (Vidal *et al.*, 2013).

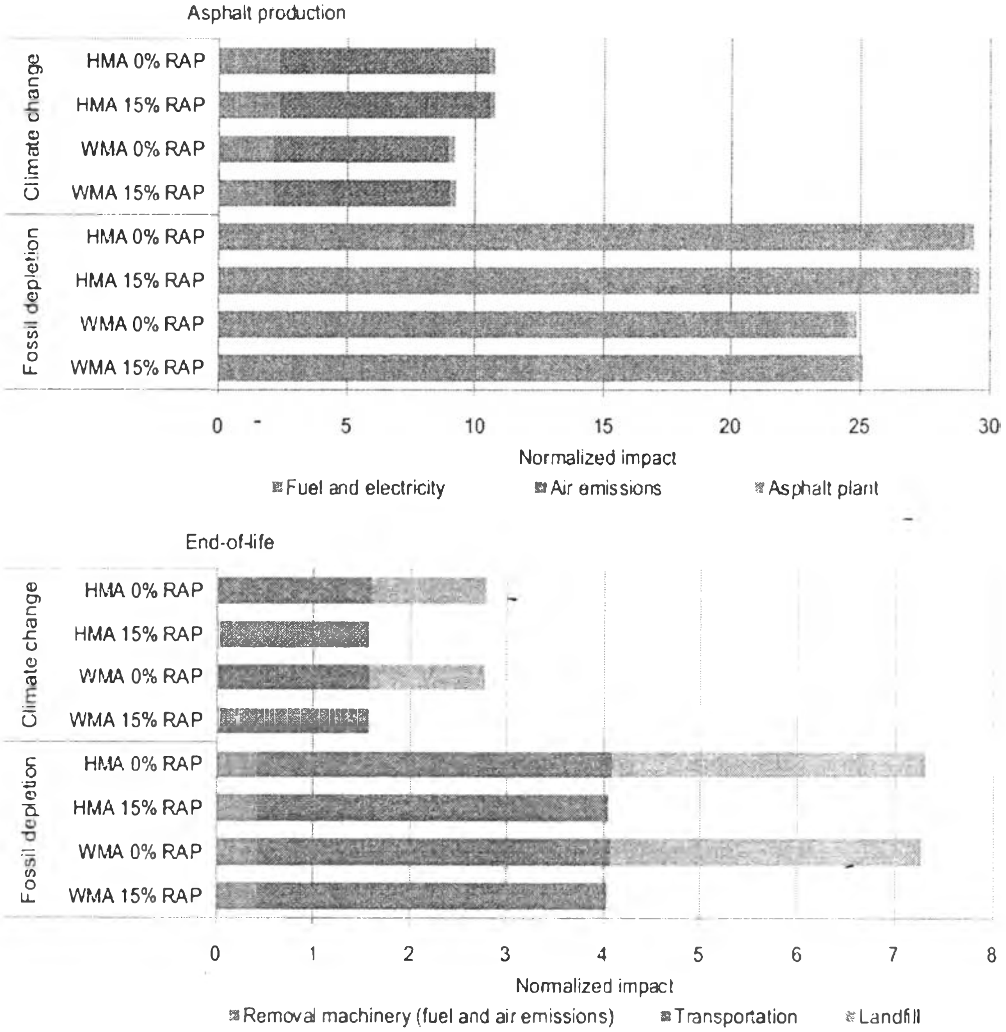


Figure 2.30 Impacts on climate change and fossil depletion of asphalt production and end-of-life (Vidal *et al.*, 2013).

NICUŢĂ* (2011) aims at pointing out the environmental impact of asphalt mixtures in a life cycle assessment (LCA) perspective and the importance of computer software as technology that facilitates this type of research. The analysis is based on the comparison between recycled versus traditional asphalt mixtures from the point of view of their ecological impact, expressed in kg CO_2 emissions/ton of mixture. The technology used for evaluation is TRL (Transport Research Laboratory) software, ASPECT (asphalt Pavement Embodied Carbon Tool) which analyses in a "cradle to site" perspective the asphalt mixtures following the LCA methodology procedures. The present analysis result are that, by adopting the recycling technology for the existing deteriorated asphalt pavements, can be obtained significant reduction (40% for the current case) of CO_2 emission on the road projects.

Santero *et al.* (2011) analyzed the pavement LCA, within pavement LCAs, traffic delay, rolling resistance, concrete carbonation, pavement albedo, lighting, leachate, and end of life allocation are areas where the supporting science is incomplete or is ineffectively incorporated into the pavement LCA framework. These components produce quantitative gaps in the assessment methodology of their previous research. For the result, LCA provides a valuable opportunity to decrease the environmental footprint associated with a vast and essential infrastructure system. Improving the deficiencies in existing LCAs and supporting research fields will undoubtedly serve to improve environmental performance and help guide transportation agencies and other stakeholders towards sustainability solutions. Exploiting the current knowledge and building upon what has already been done is the key next step to making pavement LCAs a viable and comprehensive approach to reducing environmental impact.