CHAPTER II
THEORETICAL BACKGROUND AND LITELATURE REVIEW

2.1 Asphalt

2.1.1 Definition

Asphalt is dark brown to black, thick, viscous mixture of heavy hydrocarbons that occurs naturally (left after evaporation of lighter hydrocarbons, as in Trinidad's Pitch Lake) or as a residue of crude oil refining or destructive distillation of coal. Its ability to flow when heated, moisture repellency, and (depending on the type of additive) a range of softening points (usually between 57°C to 99°C, or about 135°F to 210°F) makes it an ideal material for road paving, roofing, and water proofing applications. Also they called bitumen, coal tar, pitch, or tar.

2.1.2 General Information

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.

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 bitumens contain sulfur and several heavy metals, such as nickel, vanadium, lead, chromium, mercury, arsenic, selenium, and other toxic elements. Bitumens 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.

2.1.3 Application of asphalt

The asphalt used in the way, it can be divided into the following steps.

- Surface Preparing
  - Prime coat (Figure 2.2)
  - Tack coat(Figure 2.3)
- Surface Pavement
  - Hot-Mix Asphalt or Asphaltic Concrete
  - Cold-Mix or Cold Mixed Asphalt
- 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
- Pavement Recycling
- Patching or Deep Patching

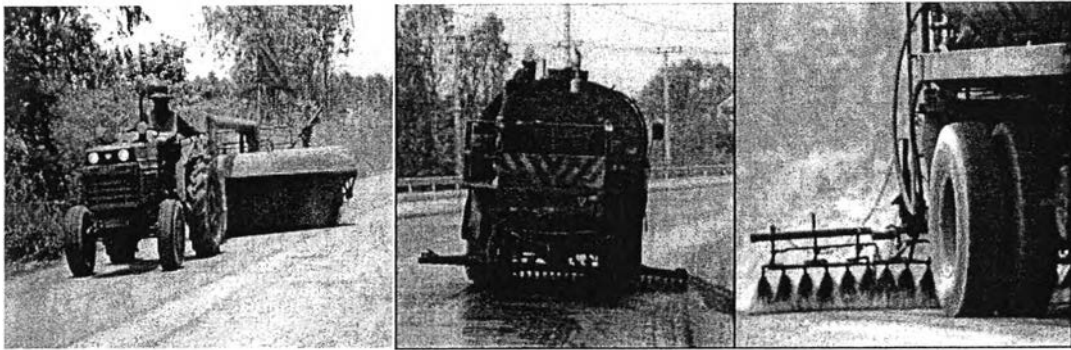**Figure 2.1** The cross section of the road.
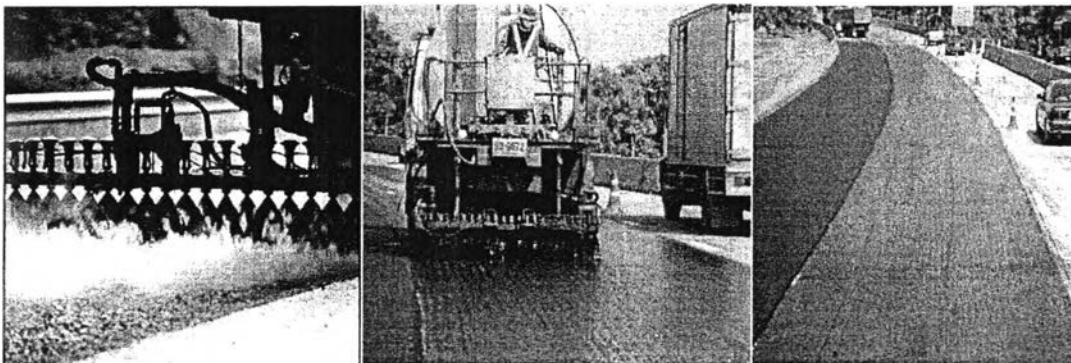
Figure 2.2 Prime coat.

Figure 2.3 Tack coat.

Procedures of pavement have 5 steps as illustrated in Figure 2.1.

- Tack coat
- Laying
- Steel wheeled Tandem roller compaction (Figure 2.4)
- Pheumatic-tired compaction (Figure 2.4)
- Let it cool and then opened to traffic

Figure 2.4 Laying and Steel wheeled Tandem roller compaction.

2.2 Hot-Mixed Asphalt (HMA)

Hot-mixed asphalt 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 mix plants or batch mix plants, according to the process by which the raw materials are mixed. In a batch mix plant, the aggregate is dried first then transferred to a mixer where it is mixed with the liquid asphalt. In a drum mix 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 emptied into haul trucks, which transport the material to the job site.

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 History of Warm-Mixed Asphalt

The concept of using lower temperatures to produce asphalt mixes is not new. First attempt to produce asphalt with bitumen that was formed by steam was carried out in 1956 by Prof. Ladis Csanyi at Iowa State University, US Since then foaming technology has been used in different countries, including US, Australian Europe. For the last twenty years, waxes have been used as viscosity modifier in Germany; initially they were not used for lowering the temperature, but for better workability of mastic asphalt and only about fifteen years ago, reduction of production and paving temperatures was declared a priority. Fischer-Tropsch wax, fatty acid amide and montan wax were used as viscosity changing additives in Germany. Modern foaming technologies were introduced at the same time as experiments with zeolite started in Germany and Shell Bitumen patented a foaming technology that was later developed as WAM-Foam.

Since then, different new foaming principles have been introduced to the market that allows reduction in production temperature even below the boiling point of water. The newest warm-mixed asphalt (WMA) production technology that involves chemical modification of the bitumen was developed in US and is known as Evotherm. It was followed by different modifications of the same technology as well as new chemical additives from other companies. Since the start of developing modern WMA

technologies, a lot of experiments have been carried out to establish potential benefits of using WMA and evaluating the performance compared to traditional Hot-Mixed Asphalt (HMA). First research reports are from Europe from 1990 and starting from 2002 a lot of testing and field trials have been conducted in US with publically available reports.

2.3.2 Benefits of Warm-Mixed 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 (Chowdhury and Button, 2008). However, the main benefits/advantages of using WMA over HMA are discussed below.

2.3.2.1 Environmental Benefits

- Reduced consumption of non-renewable fossil fuels and greenhouse gas emissions

    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 (NO_x), while the emissions of sulphur dioxide (SO_2) and VOC's (volatile organic compounds) varied above and below those of HMA.

- Reuse of by-products which would otherwise require disposal

    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.

Using these products therefore has a direct environmental benefit of reducing waste materials and also pollution from the production of other WMA specific additives.

- Increased potential for recycling Recovered Asphalt

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.

2.3.2.2 Health Benefits

- Improved conditions for workers and neighboring communities

The reduced fuel burned at the mixing plant and the lower mix temperatures during production and paving reduce emissions of aerosols, fumes and dust, both at the mixing plant and the paving site, and improve conditions for both the workers and the neighboring communities.

Investigations into emissions at paving sites in the USA found that where temperatures were reduced by 29°C to 43°C, the average reduction in total particulate matter (TPM) was between 67% and 77%, while the asphalt fumes, measured as benzene-soluble matter (BSM), was reduced by between 72% and 81%, compared to the HMA control.

General worker safety is improved as a direct result of lower asphalt temperatures that reduces the risk of heat related injuries.

At the paving site, a reduction in mix temperature of 30°C in South Africa's hot summer months is very noticeable and welcomed along with the reduced odors produced by the mix.

- 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 job sites, 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.

2.3.2.3 Engineering and Economic Benefits

The engineering and economic benefits of using WMA derive mainly from three aspects.

(1)   All WMA technologies have to provide better asphalt mix workability than HMA to achieve the required compaction at lower temperatures.

(2)   WMA's lower mixing and compaction temperatures, compared to HMA, result in flatter thermal gradients between the mix and both ambient and road temperatures. WMA therefore takes longer to cool from mixing to compaction temperature than HMA, thus providing a longer "compaction window" with many engineering advantages over HMA.

(3)   WMA's lower mixing temperatures result in comparatively less binder aging during mixing and paving than HMA.

The 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 compact ability 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 burner fuel consumption

Lower plant mixing temperatures should result in reduced fuel consumption, the extent of which depends on many factors, some of which include:

– The temperature of the WMA in relation to HMA.

– The moisture content of the aggregates and RA (fuel usage is reported to increase by around 10% for every 1% increase in moisture content).

– The efficiency of the mixing plant's burner, exhaust and emission systems

– Rapid changes between the production of WMA and HMA that required the plant to stabilize at the different operating temperatures.

NAPA reports an average 23% fuel saving, with results ranging from 15.4% to 77% reduction in fuel usage.

The WMA trials in South Africa were too short and interspersed with the production of conventional hot-mixed to measure fuel consumption figures accurately enough to draw conclusion. Nevertheless it can be concluded that there were indeed fuel savings as the plant's burners were turned down in order to produce the mix at the required lower temperatures.

- 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 life cycle costs and using less non-renewable resources. The extent of the reduced life cycle costs will have to be verified by long-term pavement performance measurement. Ingredients of some WMA additives have an additional anti-aging effect.

- Synergy between WMA and asphalt recycling processes

The softer binder resulting from the lower temperatures used in the manufacture of WMA may assist in rejuvenating the aged binder in the RA, thereby improving the mix's fatigue properties. The WMA technology will also improve the compatibility of stiffer mixes that may result from the incorporation of high proportions of RA.

WMA mixes containing up to 40% RA, using both penetration grade bitumen and A-P1 as well as A-E2 binders have been successfully produced and paved in trials in South Africa, while higher percentages of RA, even up to 90% and 100%, with the addition of rejuvenating oil compounds, have been achieved in Germany with manufacturing and paving being carried out at conventional HMA temperatures.

- 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 Drawbacks of Warm-Mixed Asphalt

- Rutting

    Rutting is mainly caused by the less aging 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; Corrigan, 2009).

- 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 aging 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 (Diefenderfer and Hearon, 2008).

- 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 and Prowell, 2005; Hurley and Browell,2005; Hurley and Prowell, 2006). 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 and Amirkhanian, 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).

- 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 and Button, 2008), and in Europe the trial sections of WMA have performed as well as or better than HMA overlays (D'Angelo*et al.*, 2008). It is important to highlight that, whereas in the USA tests have been performed by public organisms (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.

- 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.

- Quantitative life-cycle analysis (QLCA)

Evidently, a QLCA is needed in order to assess pavement sustainability and promote WMA technologies (Miller and Bahía, 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.

2.3.4 Warm-Mixed Asphalt Technologies

2.3.4.1 Classification of WMA Technologies

The WMA technologies can be classified in several ways. One is to classify the technologies by the degree of temperature reduction. Warm-Mixed Asphalt (WMA) is an asphaltic mixture made using a wide range of technologies that allow for production and placement at temperature of the WMA at the time of production shall be below T_{max}-50°C, Where T_{max} is the maximum allowable production temperature of HMA. WMA technologies may be used as a compaction aid to extend the paving season in colder climates when produced at a range of temperature up to those

typical for HMA production. A WMA technology may include an additive, specialty equipment, or both. The words "bituminous concrete", in the Standard Specifications and other documents referenced by this specification, shall apply to "Warm-Mixed Asphalt" and "WMA". WMA can be conveniently classified by the degree of temperature reduction compared to that of conventional HMA. This is illustrated in Figure 2.5, which shows the typical ranges in mix temperature, from cold mixes to conventional hot-mixed asphalt (HMA). It also shows the consumption of fuel increases in order to produce mixes at higher temperatures. If the production temperature is less than 100°C (212°F) it is considered as a "half-warm" mix. Generally WMA is regarded to have production temperatures at least 20°C below those of HMA, and above 100°C. While HMA is generally manufactured at temperatures between 140°C and 16°C, WMA is typically produced at temperatures between 100°C and 140°C (Solomons*et al.*, 2011).
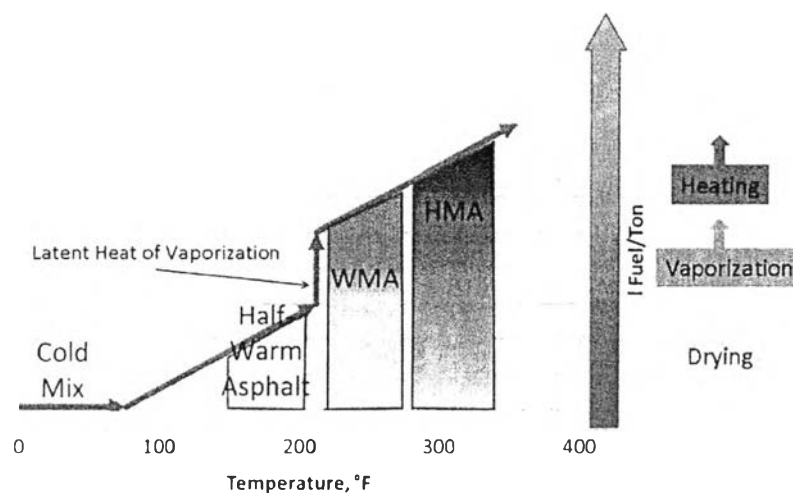

Figure 2.5 Typical temperature ranges for mixes, from cold mixes to conventional HMA.

Another way to classify WMA is by the technologies used to reduce temperature. This classification method allows for a more descriptive discussion of the process. No general or commonly used technology classification was found during the literature review. The following classification was made after making an overview of

technologies on the market, by generalizing the different terms used in other studies and after consultation with chemical engineers to meet the producing technique adequacy to technology classification. Three different techniques were found:

- Foaming techniques (which are divided into water-based and water containing)

- Organic or wax additives

- Chemical additives

All of the existing products use at least one of these technologies, but there may be combination of them as well.

2.3.4.1.1 Foaming process

This technology mainly entails the addition of small amounts of water, either injected into the hot binder or directly into the mixing chamber (Larsen, 2001). When the water is mixed with the hotbitumen, high temperatures cause it to evaporate and the steam isentrapped. This generates a large volume of foam, which temporarily increases the volume of the binder and reduces mix viscosity. This effect remarkably improves the coating and workability of themix, but its duration is limited. This means that the mix must be spread and compacted soon after production. These methods have been tested for soft and medium bitumen grades (Butz *et al.*, 2001). Special precautions must be taken when adding water. In otherwords, the quantity of water should be just enough to produce the foaming effect, but not so much as to cause a stripping problem (Smith, 2007).

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) (Zaumanis, 2010).

- Water-containing technologies

Water-containing technologies use synthetic zeolite to producethe foaming process. The product 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 micro-foaming effect in the asphalt mix (Smith, 2007), which lasts about 6-7 hour (Chowdhury and Button, 2008; D'Angelo *et al.*, 2008). 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 crystallinestructure is the main characteristic of this silicate framework (Chowdhury and Button, 2008).

- Water-based technologies

Water-based technologies use water in a more direct way. This means that the water needed to produce the foaming effect isinjected 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 (Zaumanis, 2010)

• Double Barrel Green, Ultrafoam GX, LT Asphalt: Although the equipment for injecting water into the hot binder streamdiffers (since each company makes its own equipment), the basic principle is the same. Several nozzles are used to inject the cold water to microscopically foam the binder.

• WAM Foam: This is a two-component binder system (also known as a two-phase method) that feeds a soft binder anda hard foamed binder at different times into the mixing cycleduring 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 ofthe hard binder, along with the foaming of the hard bitumen, reduces mix viscosity to provide the necessary workability.

There are other technologies that use water differently, and thus do not fall into either category. One example is Low Energy Asphalt which uses wet fine aggregate. The foaming effect is produced at contact with the hot binder when aggregate of a certain particle size is partially dried. Such technologies are based on a process known as sequential mixing. The final water content is usually around 0.5% at 95°C, which guarantees workability and a sufficient level of compaction (D'Angelo*et al.*, 2008; Bueche, 2009).

In 2007, McConnaughay developed Low Emission Asphalt. LikeLow Energy Asphalt, it is a combination of chemical and foamingtechnology. The mixing process also occurs in two phases. In the first phase, the binder containing a chemical additive is added tothe hot coarse aggregates, and in the second phase, wet sand is added which creates a foaming action (Hamzah*et al.,* 2010).

2.3.4.1.2 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, they tend to increase the stiffness of the binder and asphalt's resistance against deformation. The type of wax must be selected carefully so that the melting point of the wax is 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.

- Example of organic additives - 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 waxes and 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 aging stability, and can be stored indefinitely (Hurley and Prowell, 2005).

- Example of organic additive - fatty acid amid

Fatty acid amides are synthesized long-chainaliphatic hydrocarbons. 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 forma homogeneous

solution with the base bitumen and produce a marked reductionin the bitumen's viscosity during its liquid state.

During cooling the fatty acid amides crystallizeand form crystallites in the bitumen,thus increasing asphalt stabilityand its deformation resistance.

- Example of additive - Montan wax

The difference between naturally occurring bituminous waxes and 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 and Prowell, 2005).

2.3.4.1.3 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.

2.3.4.2 Summary of WMA products

The most widely used products available on the market and their descriptions are listed in Table 2.1. It also contains the reported regions of the use for corresponding products from the literature. As the reported values of production temperatures were not the same in all the reports, the most commonly reported data ordata supported by the production company are listed first and the data from different research after. The differences in the reports may be caused by different factors, such as type and the amount of additives used, humidity of materials, mix design method, climatic conditions, materials used, etc. The amount of WMA additive usually depends on the materials used, their proportion and especially the grade and type of bitumen used.

Table 2.1 Summary of WMA products description (Zaumanis,2010)

Product	Company	Description	Reports from countries	Additive	Production temperature [or reduction ranges]
FOAMING TECHNOLOGY					
Aquablack WMA	MAXAM equipment	Water based foaming process	U.S.	Not necessary	Not specified
Double Barrel Green	Astec	Water based foaming process	U.S.	By choice, Anti-stripping agent	116-135 °C 120 °C
Low Energy Asphalt	LEACO	Water based Hot coarse aggregate mixed with wet sand	U.S, France, Spain, Italy	Yes, ±0.5% of bitumen weight of coating and adhesion additive	≤100 °C 105-124 °C
Low Energy Asphalt	McConnau-ghay Technologies	Combination of chemical and water based foaming technology	U.S.	Yes, 0.4% of bitumen weight	90 °C >100 °C
Ultrafoam GX	Gencor Industries	Water based foaming process	U.S.	Not necessary	Not specified
WAM-Foam	Shell and Kolo-Veidekke	Foaming process using two binder grades	U.S, Norway	Antistripping agents could be added to soften binder	110-120 °C 100-120°C 62 °C
Warm-Mixed Asphalt System	Terex Roadbuilding	Water based foaming process	U.S.	Not necessary	[<32°C]
LEAB	BAM	Water based Mixing of aggregates below water boiling point	Netherlands	0.1% of bitumen weight of coating and adhesion additive	90 °C
LT Asphalt	Nynas	Water based Binder foaming + hygrophilic filler	Italy, Netherlands	0.5-1.0% of hygroscopic filler by mixture weight	90 °C
Advera	PQ Corporation	Water containing using Zeolite	U.S.	0.25% by mixture weight	[20-30 °C]
Aspha-Min	Eurovia	Water containing Zeolite	U.S, France, Germany	0.3% by mixture weight	30 °C [20-30 °C]

Product	Company	Description	Reports from countries	Additive	Production temperature [or reduction ranges]
ORGANIC					
Sasobit	Sasol	Fischer-Tropsch wax	U.S, EU, worldwide	2.5-3.0% of bitumen weight in Germany 1-1.5% of bitumen weight in US	[10-30 °C] [20-30 °C] [18-54 °C] 130-150 °C
Asphaltan A Romonta N	Romonta GmbH	Montan wax for mastic asphalt	Germany	1.5-2.0% of bitumen weight	[20 °C]
Asphaltan B	Romonta GmbH	RafinedMontan wax with fatty acide amide for rolled asphalt	Germany	2-4% by mixture weight 2.5%by mixture weight	[20-30°C]
Licomont BS 100	Clariant	Fatty acid amide	Germany	3% of bitumen weight	[20-30°C]
3E LT or Ecoflex	Colas	proprietary	France	Yes, not specified	[30-40 °C]
CHEMICAL					
Evotherm ET	Mead-Westvaco	Chemical bitumen emulsion	U.S. France, worldwide	Delivered in form of bitumen emulsion	[50-75 °C] [37-54 °C] 85-115 °C
Evotherm DAT	Mead-Westvaco	Chemical package plus water	U.S, France, worldwide	30% by weight of binder	[45-55 °C] >93 °C 85-115 °C
Evotherm 3G	Mead-Westvaco	Water free chemical package	U.S.	Not Specified	[33-45 °C] [15-27°C]
CECABASE RT	CECA Arkema group	Chemical package	U.S, France	0.2-0.4% by mixture weight	120°C 101°C
Rediset WMX	Akzo Nobel	cationic surfactants and organic additive	U.S, Norway	1.5-2% of bitumen weight	[≥30 °C] [16 °C] 126°C
REVIX	Mathy-Ergon	Surface-active agents, waxes, processing aids, polymers	U.S.	Not speccified	[15-26 °C]

2.4 Life Cycle Assessment (LCA)

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

2.4.1 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 (Russell *et al.*, 2005). 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.

2.4.1.1 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 (Guinée *et al.*, 2010). In Europe, early LCA-like work started soon afterwards in Germany, England, Switzerland, and Sweden (Klöpffer, 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 (Guinée *et al.*, 2010). In the late 1980s, not only packaging, but also many other systems were gradually studied and analyzed from "cradle to grave" (Klöpffer, 1997). 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.

2.4.1.2 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). Many scientific journal papers have also been published. In the early 1990s, through its North American 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.

2.4.2 Definition of LCA

Two of the most widely accepted definitions of LCA are presented below as they have been chronologically formulated to date.

2.4.2.1 Definition of LCA by SETAC

"The life cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing; transportation and distribution; use, re-use, maintenance; recycling; and final disposal."

2.4.2.2 Definition of LCA by ISO 14040

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

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".

2.4.3 LCA Methodology

The Society of Environmental Toxicology and Chemistry's (SETAC) "Code of Practice", which can be illustrated by the famous SETAC triangle shown in Fig.2.6, originally distinguished four methodological components within LCA: goal and

scope definition, inventory analysis, impact assessment, and improvement assessment (Rebitzer *et al.*, 2004).
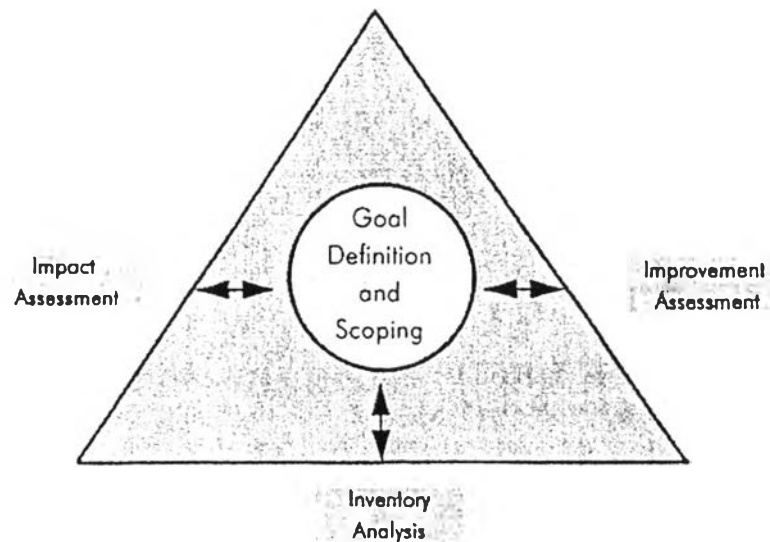
Figure 2.6 SETAC triangle (Klöpffer, 1997)

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 Fig.2.7. In practice, an LCA is often conducted iteratively, repeating some of the phases several times in order to eliminate uncertainties (Widheden and Ringström, 2007).
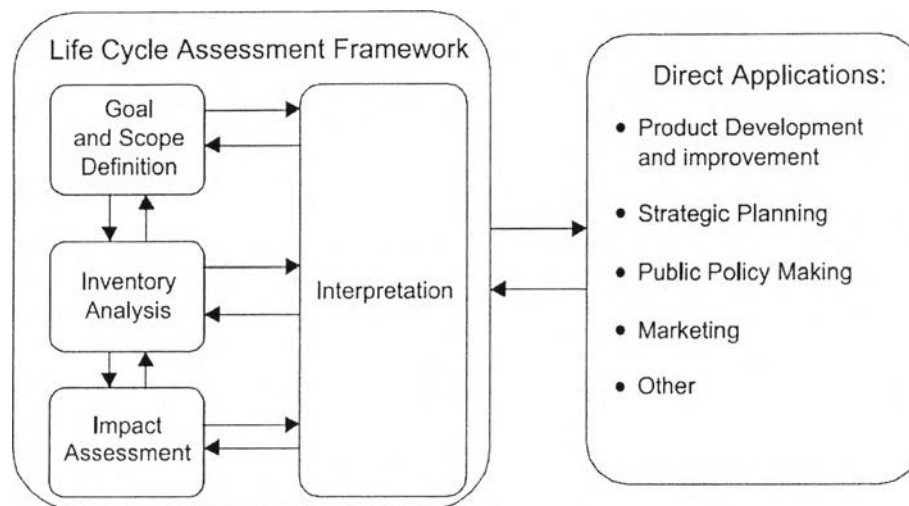
Figure 2.7 General methodological framework of LCA.

2.4.3.1 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 and Ringström, 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 concern to 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 of the product system being analyzed.

2.4.3.2 Inventory Analysis

Life Cycle Inventory (LCI) is the phase of the LCA involving the compilation and quantification of inputs and outputs; it comprises data collection and data calculation. Data collection consists of the identification and quantification of the relevant input and output flows for the whole life cycle of a product.

Basically three types of flows can be differentiated: elementary flows (emissions, resources) that are emitted into the environment or extracted from it, product flows (goods, services), that come from or go to the techno sphere, and waste

flows (a sub-type of product flows). The use of resources and the use of land, raw materials, fabricated products, auxiliary materials, energy carriers and electricity are recorded as inputs. Emissions to air, water and land as well as wastes and by-products are outputs in an inventory analysis. In the later stage of the impact assessment, the quantitative information on the product system's elementary flows (and in some methods the waste flows) is used to analyze the product's impacts.

The most important steps of life cycle inventory work are determination of the reference quantity (e.g. functional unit, reference flow), description of system in flow diagrams, identification of unit processes to be modeled separately in LCI model, qualitative determination of inputs and outputs, quantitative determination of inputs and outputs, documentation of the type of data survey, inventory data collection, inventory data collection of transport, and Calculation of the inventory, including allocations and covering the inventories of the background data sets(Jensen, 1997).

2.4.3.3 *Impact Assessment*

The impact assessment is carried out on the basis of the inventory analysis data. It is the third phase in a life cycle assessment containing the following main issues (Bianchi, 2008):

• Category definition

The impact assessment categories should link the potential impacts and effects on what is referred to as the "areas of protection" of the LCA, i.e. the entities that we want to protect by performing and using the LCA. Today, there is acceptance that the protection areas of life-cycle assessment are:

> ➢ natural resources
> ➢ natural environment
> ➢ human health
> ➢ and often also: man-made environment

• Classification

In the classification step the inventory data are assigned to categories according to their impact. For instance, carbon dioxide emissions contribute to the greenhouse effect and are hence assigned to the impact category Climate change. If a substance contributes to several impact categories, it has to be taken into account in all of these categories. Such a case is, for example, nitrogen oxide that causes both eutrophication and acidification.

• Characterization

Classification is followed closely by characterization. Every substance is assigned a potential impact in the impact category under study. The potential impact of a substance is given relative to a dominant factor in the category, e.g. for the Climate change potential this is typically 1 kg of carbon dioxide emissions. These relative impacts (the characterization factors of a substance) are than multiplied with the amount of each emission and the resulting impact values are summed for the respective impact category.

Life Cycle Impact Assessment uses generally the following categories:

- Greenhouse effect (or global warming potential)

Global warming is called the greenhouse effect because the gases that are gathering above the earth make the planet comparable to a greenhouse. By trapping heat near the surface of the earth, the greenhouse effect is warming the planet and threatening the environment. The climate changes that will result from global warming are extremely difficult to predict. If temperatures do indeed rise significantly, the most important result would be that some portion of the polar icecaps would melt, raising global sea levels.The Global Warming Potential (GWP) is the potential contribution of a substance to the greenhouse effect. This value has been

calculated for a number of substances over periods of 20, 100 and 500 years because it is clear that certain substance gradually decompose and will become inactive in the long run.

- Ozone layer depletion

The ozone layer is essential to life on earth, as it absorbs harmful ultraviolet-B radiation from the sun. Every time 1% of the ozone layer is depleted, 2% more UV-B is able to reach the surface of the planet. The increasing of ultraviolet-B is one of the most harmful consequences of ozone depletion because it can cause skin cancer. Ozone Depletion Potential (ODP) values have been established mainly for hydrocarbons containing combined bromine, fluorine and chlorine, or CFCs. Here too, one of the substances (CFC-11) has been adopted as a reference.

- Acidification

The Acidification Potential (AP) is expressed relative to the acidifying effect of SO_2. Other known acidifying substances are nitrogen oxides (NO_x), sulfuric acid (H_2SO_4), and hydrogen chloride (HCl).

- Eutrophication

Eutrophication is an increase in the concentration of chemical nutrients (nitrogen (N) and phosphorus (P)) in water bodies, often leading to changes in animal and plant populations and degradation of water and habitat quality. The Nutriphication Potential (NP) is expressed as kg phosphate (PO_4) equivalents. Other emissions also influence eutrophication, notably nitrogen oxides and ammonium.

2.4.3.4 Interpretation

Within the framework of an evaluation, the results from the impact assessment and the inventory analysis are analyzed and conclusions and

recommendations are established. A further aspect is the transparent presentation of the LCA results. The ISO standards comprise three interpretation elements (Bianchi, 2008):

- Significant issues

  In order to determine the significant issues the main contributions of each impact category have to be identified (which emissions and/or which processes are dominant within each category). The relevant inventory data which cannot be recorded through impact categories must also be integrated into the study. Following the scope definition, the main contributions can be grouped by the individual process step, individual life phases and the entire life cycle. Together with these results, the significant issues can now be established, since it is now also clear which processes or life phases are dominant.

- Results evaluation

  To evaluate the results according to the ISO standard, a completeness check, a sensitivity check, and a consistency check of the identified processes or life phases must be carried out. Completeness is checked by e.g. a mass and energy data analysis and considering experts' know-how of the modeled processes. Sensitivity is determined by calculating scenarios for different processes or different parameters (e.g. varying yield of processes and emission factors). The effects of the different assumptions on the total result show the sensitivity.

  It must be ensured that all necessary information and data relevant to the interpretation are available and complete; for confidentially needs or process operators the ISO standards foresee to establish respective agreements. It is also important to check to what extent uncertainties, for example through the estimation of data due to data gaps, may influence the result. The consistency check should ensure that the procedure is consistent with the goal and scope definition and that the methodology and other rules have been accurately and consistently applied for the whole product system.

- Conclusions and recommendations

The aim of this third step of the interpretation is to reach conclusions and recommendations for the report of the LCA study or life cycle inventory study.

This step is important to improve the reporting and the transparency of the study. Both are essential for the readers of the LCA report.

The results of the critical review of the study shall also be included when presenting the conclusions and recommendations.

2.4.4 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.

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 and Ringström, 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 product.

2.5 LCA Studies of Warm-Mixed Asphalt

Zhen Leng and Imad Al-Qadi (2011) : Study the LCA of WMA compared to traditional HMA. Specifically, the environmental and economic performance of the following two mixtures were evaluated and compared 1) a warm stone mastic asphalt (SMA) binder course mixture with a chemical additive and 2) a control hot SMA binder course mixture. A life cycle inventory (LCI) was developed to quantify the energy, material inputs, and emission during aggregate and asphalt binder production, and mixture plant production, transportation, and placement. Subsequently, the lifecycle model was applied to compare the environmental impacts and the economic costs(agency cost and user cost) of the control SMA mixture and the warm SMA mixture. Then environmental impacts of factors such as global warming, air pollutants, etc. were computed using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) developed by the US Environmental Protection Agency (USEPA 2008). Finally, the overall performances of the control SMA and the warm SMA were compared by calculating a weighted environmental and economic score and the total cost (environmental, agency, and user costs). The results of this study indicate that the warm SMA provides significant environmental benefits compared to the control hot SMA. When the mixing temperature was decreased from 325 to 280 °F (168 to 138 °C), the overall environmental impact of the material, production, transportation, and placement was reduced by 6.4% due to the use of warm mix additive.

G. F. A. Ball (2010) : Gives a summary of developments in warm asphalt manufacture up to 2009, and has the following objectives: 1. Summarize research and trials carried out overseas and in New Zealand with the various methods of producing asphalt mixes. 2. 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. 3. Compare costs of setting up and production. 4. Investigate if any particular methodologies are particularly suited to the New Zealand situation. 5. 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.

Butt (2012) : In this work, an open LCA framework is suggested for quantifying energy and environmental loads during construction, maintenance and end of life phases of a given asphalt pavement. A method to calculate feedstock energy of bitumen is developed and a method to quantify mass-energy flows of additives is described. If the production data of additives is available, an energy-mass flow of any asphalt additive can be calculated based on the method suggested. Case-studies were performed to demonstrate the use of the LCA framework. The suggested LCA framework was demonstrated in a limited case study (A) of a typical Swedish asphalt pavement. Sensitivity analyses were also done to show the effect and the importance of the transport distances and the use of efficiently produced electricity mix. It was concluded that the asphalt production and materials transportation were the two most energy consuming processes that also emit the most Green House Gases (GHG's). Case study B was shown how polymer modification for improved performance affects the energy consumption and emissions during the life cycle of a road. From the case study (C) it was concluded that using bitumen with self-healing capacity can lead to a significant reduction in the GHG emissions and the energy usage. Furthermore, it was concluded that better understanding of the binder would lead to better optimized pavement design and thereby to reduced energy consumption and emissions. Production energy limits for the wax and polymer were determined which can assist the additives manufacturers to modify their production procedures and help road authorities in setting 'green' limits to get a real benefit from the additives over the life time of a road.