CHAPTER II

LITERATURE REVIEW

2.1. Concept and Theory of Pavement Cold Recycling

2.1.1 The Cold Recycling Procedure

Cold recycling is a procedure mixing materials and stabilizing agents by a special recycling machine capable of grading and milling materials on a road surface of 60 cm depth. The recycling machine has been developed over the years from modified milling machines and soil stabilizers, as they are specially designed to recycle a thick pavement layer in a single pass. Modern recyclers tend to have large powerful motor, which may be either tracked mounted (2200 CR) or high flotation pneumatic types (WR 2500).

The milling process begins with water from a tanker coupled to the recycler delivered through a flexible hose into the recycler's mixing chamber. The water, control by a micro-processor pumping system, is mixed thoroughly together with the milled materials to achieve optimum compaction moisture content.

Fluid stabilizing agents, like cement/water slurry or bitumen emulsion, either individually or in combination, can also be introduced directly into the mixing chamber in a similar manner, in addition foamed bitumen may be injected into the mixing chamber, through a special spray bar.

Power stabilizing agents such as Portland cement are normally spread onto the exiting road surface ahead of the recycle. The recycler passes over, mixing it together with water into the underlying materials in a single operation.

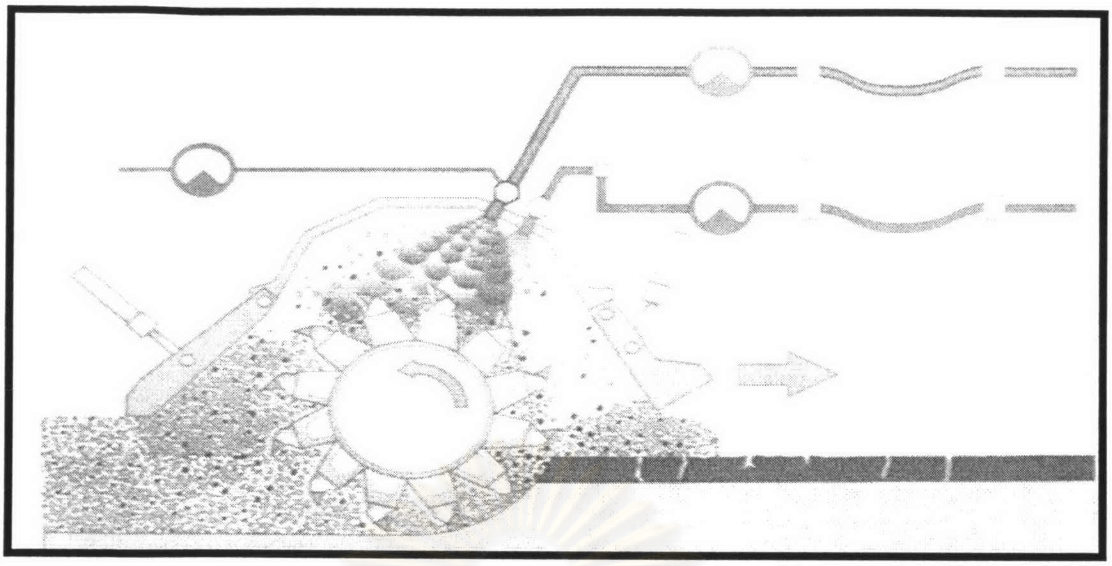

Figure 2.1 Configuration of milling / mixing drum and spray bar systems

Source: Wirtgen cold recycling manual 2001

Figure 2.1 shows the milling/mixing drum equipped with a large number of special cutting tools. The drum rotates, milling the material in the exiting road pavement.

After recycling, the materials receive an initial pass from a roller to increase the strength of material. Then it is pressed with a grader before being compacted using a vibratory roller.

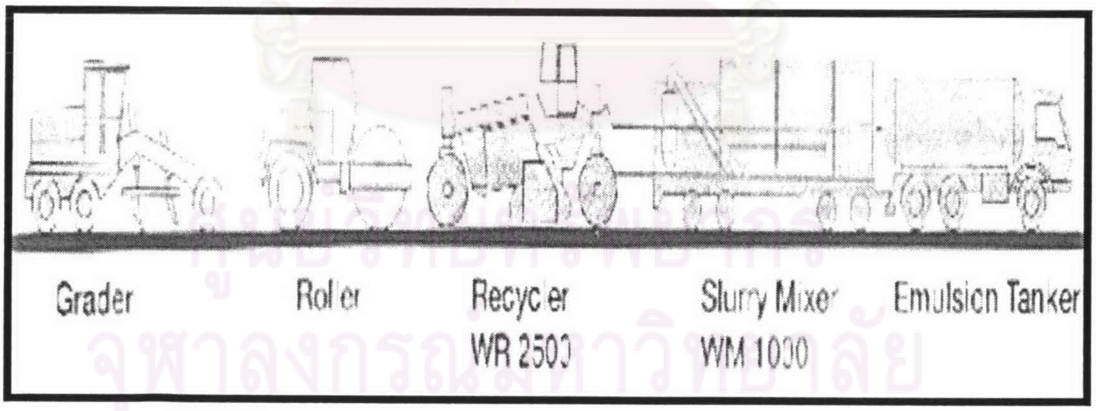

Figure 2.2 Typical recycling train with cement and bitumen emulsion using a tyre mounted machine

Source: Wirtgen cold recycling manual 2001

Figure 2.2 shows cold recycling with cement. The recycler pushes a slurry mixer ahead of it. In the slurry mixer, cement and water are mixed together at precise, predetermined quantities, and the slurry is transferred via a flexible hose and injected into the recycler's mixing chamber. Alternatively, instead of using slurry a mixer, the cement may be spread ahead of the recycling machine.

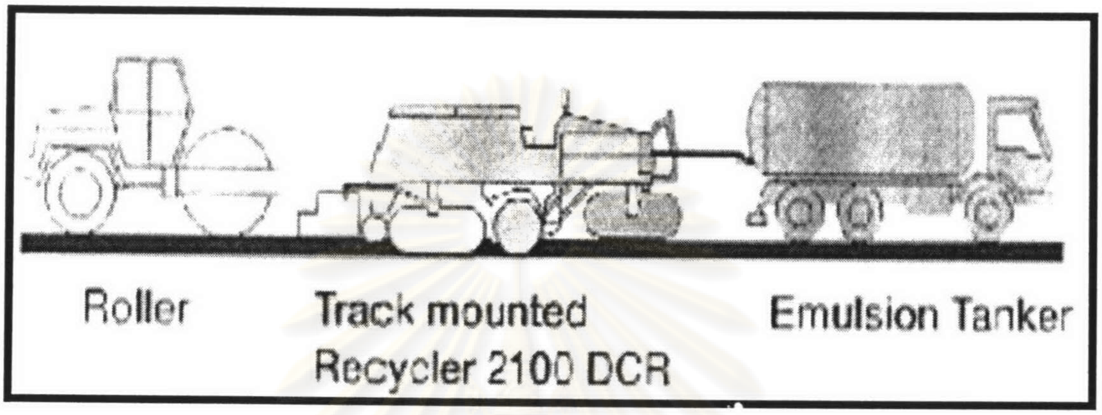

Figure 2.3 Recycling train with bitumen emulsion using track recycler

Source: Wirtgen cold recycling manual 2001

Figure 2.3 shows how bitumen emulsion is used with cement in a similar recycling train configuration, except the tanker is filled with bitumen emulsion ahead of slurry mixer. In cases where the cement is spread ahead of the recycling train, the tanker is coupled directly to the head recycler.

In this configuration, a tracked recycling machine would typically be used when carrying out thin layer recycling where the exiting pavement consists of thick asphalt layers and recycling is conducted within the thickness of the asphalt. If the recycler is equipped with a paving screen, the grader, to profile the surface, may be not necessary.

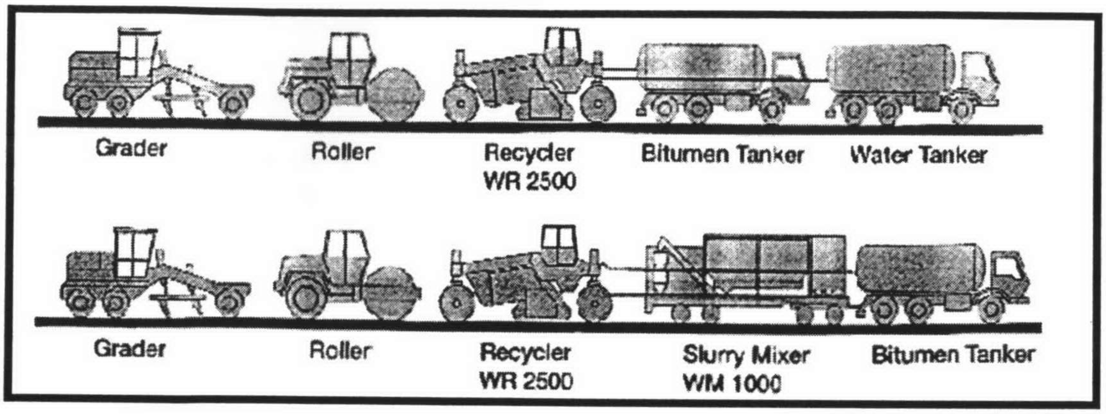

Figure 2.4 Typical recycling trains using foamed bitumen, alone and in combination with cement

Source: Wirtgen cold recycling manual 2001

Figure 2.4 shows two typical recycling trains that are used when recycling with foamed bitumen it can be used on its own, when recycling a pavement that includes asphalt and/or good quality crushed stone. The recycler pushes two tankers ahead of it; first, a tanker filled with hot bitumen and then a water tanker. When foamed bitumen and cement are used in combination, they can be added either in slurry form, using a slurry mixer, or spread in the exiting road surface ahead of the recycling train.

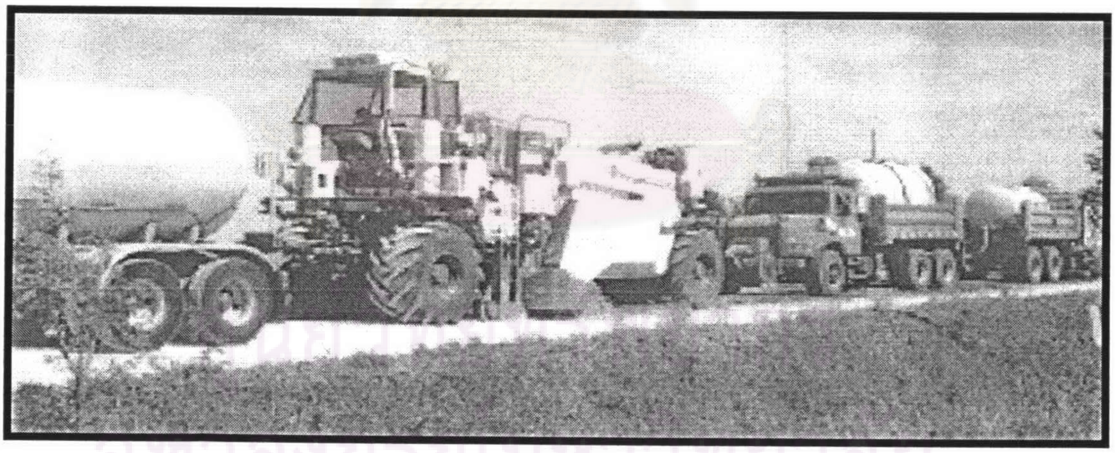

Figure 2.5 Cold in-place recycling

Source: Mike Heitzman, bituminous materials engineer, Iowa Department of Transportation (Iowa DOT)

Figure 2.5 shows typical cold in-place recycling. This is a procedure that has minimal effect on road structure because the machine can complete the work in one cycle. This is suitable for roads surface. The most important advantages of recycling are conservation of resources and money.

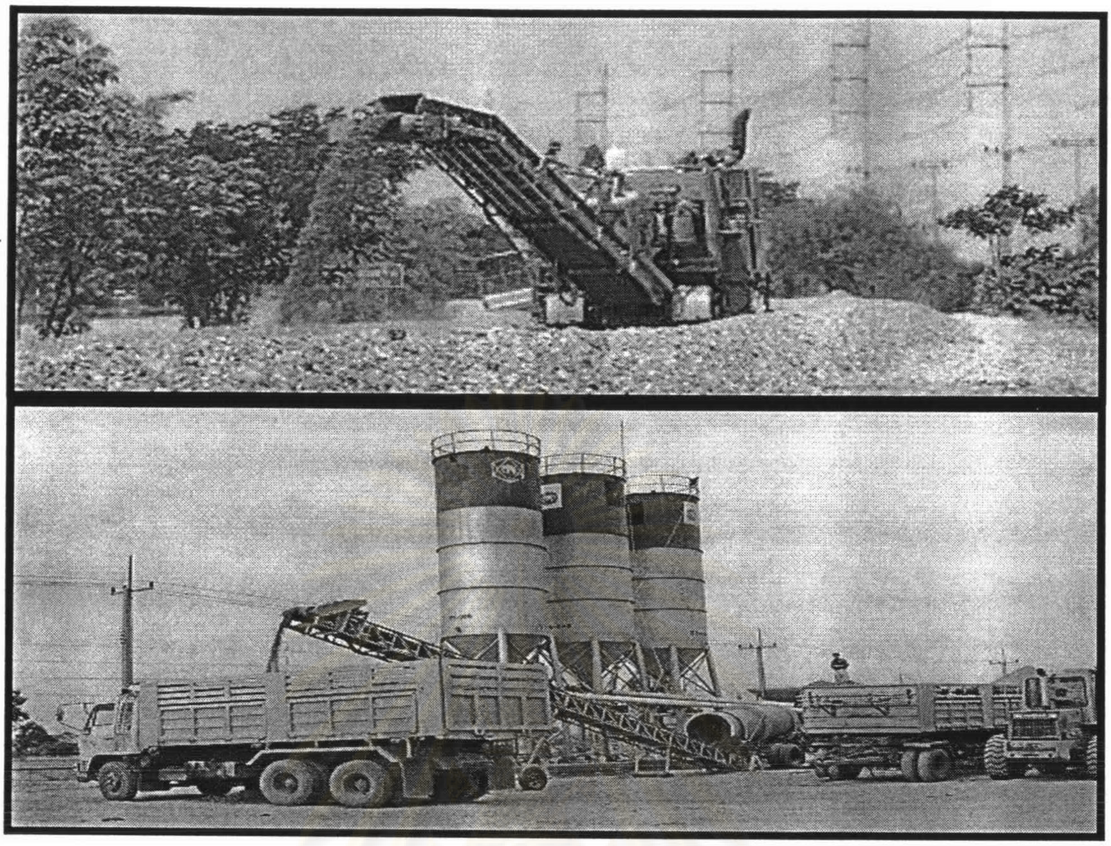

Figure 2.6 Cold in-plant recycling

Source: Phitsanulok-Uttradit October 2003

Figure 2.6 shows typical cold in-plant recycling. This method prepares the materials in a stock area first. This means mixing materials at optimum moisture, maximum dry density, best percentage of foamed asphalt or cement content and proper proportion of RAP and virgin aggregate. The most important consideration in this case is control the temperature and moisture content during movement of materials to construction site.

Figure 2.7 Mobile mix plant

Source: Gunnar Hillgren, Alan James Tomas Svenson and Thomas Wallin, 1996

Figure 2.7 shows a typical mobile mix plant in Sweden, the mix is produced in mobile mix plants placed at the site where the millings are stockpiled and used for reshaping and country roads with traffic up to 3000 vehicles per day. After recycling materials receives an initial pass from a roller to consolidate it is profiled with a grader before being compacted by a vibratory roller.

2.1.2 Equipments

2.1.2.1 Rollers

The aim of compacting a stabilized material is to reduce the voids and water, thereby, increasing the density and, thus, load carrying capacity of a layer. Single drum rollers are usually used for compaction of stabilized layers in combination with pneumatic rollers. When selecting the type and size of roller, the following should be considered.

- Roller weight/size
    - 10 to 15 ton statistic mass for compacting recycled layers up to 200 mm thick
    - 15 to 20 ton statistic mass for compacting recycled layers up to 200 to 400 mm thick.

- Frequency and Amplitude
  - Vibration frequency range from 29 to 35 Hz
  - Vibration amplitude range from 0.91 to 1.66 mm
  - Large amplitude/low frequency for the initial compaction, deep penetration of energy

Small amplitude/high frequency for the final compaction, shallow penetration of energy

Figure 2.8 shows a typical single drum roller WR 2500 recycler.

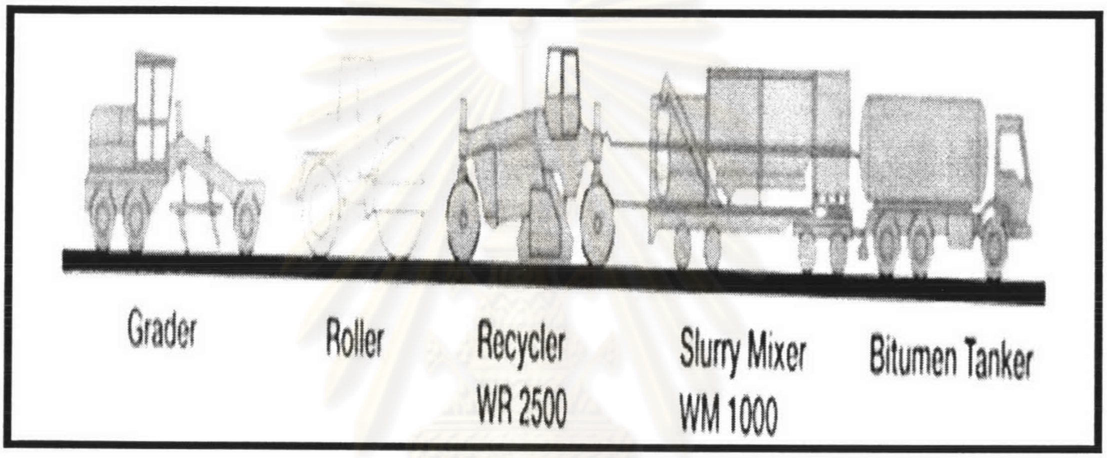

Figure 2.8 Typical of single drum roller of recycler WR 2500

Source: Wirtgen cold recycling manual 2001

2.1.2.2 Graders

These should have power enough to spread, place and level the recycled materials. As a guide the following specifications can be used

- 100 kW engine power
- 3.66 m blade length with repeatable mould board wear strips
- 610 mm blade height
- Hydraulic controls for constant speed blade positioning.

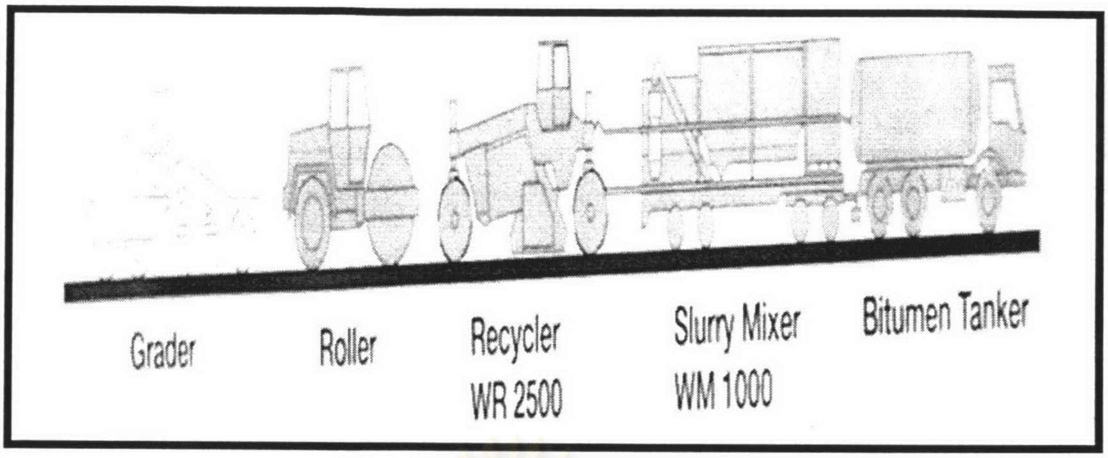

Figure 2.9 Typically of grader of cold recycler WR 2500

Source: Wirtgen cold recycling manual 2001

2.1.2.3 Bulk Spreaders

There are various types of spreaders available for applying power stabilizing agents on a road surface. Important features of all spreaders include

- Variable width to cater to recycling width vibrations of 9 overlaps)
- Capability to be calibrated (kg/in^2) to produce an accurate spread rate
- Sufficient capacity (t) for the recycling operation

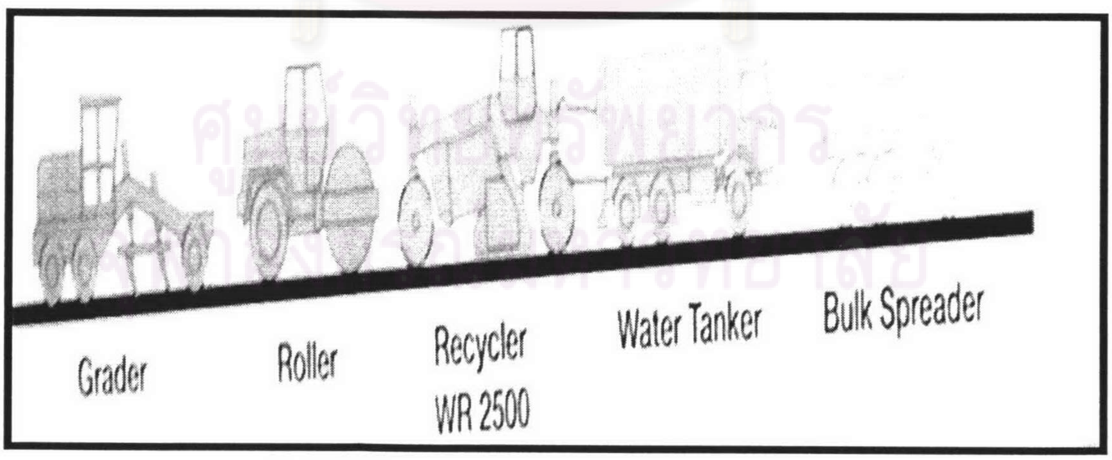

Figure 2.10 Typical of bulk spreader cold recycler

Source: Wirtgen cold recycling manual 2001

2.1.2.4 Slurry Mixer

The WM 1000 slurry mixer is generally employed where site conditions demand:

- A high degree of accuracy in the application rate of cement
- No contamination from wide-blown cement

In a composite bitumen/cement recycling train, the WM 1000 should always be placed immediately in front of the 2200 CR or WR 2500, the bitumen tanker being the lead vehicle.

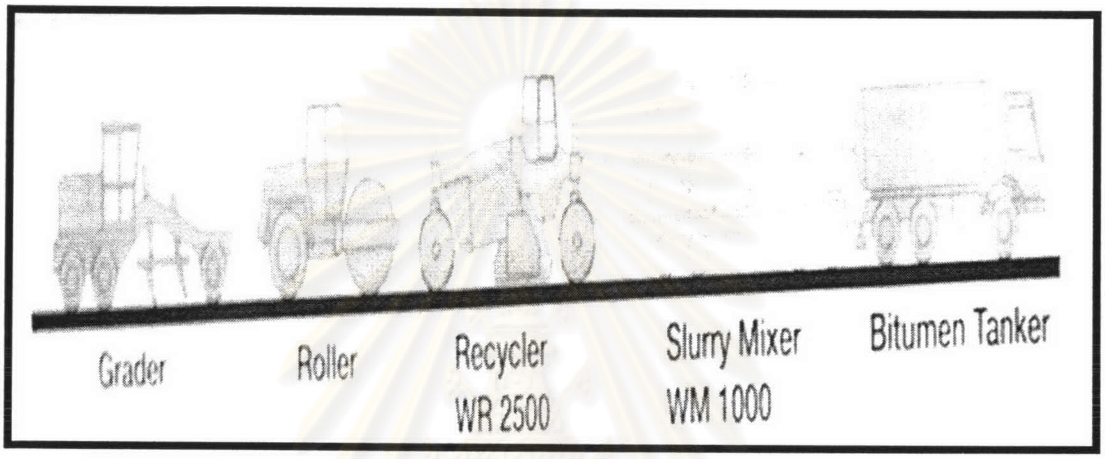

Figure 2.11 Slurry mixers WM 1000

Source: Wirtgen cold recycling manual 2001

The WM 1000 has maximum output of 1000 liters of water/cement slurry per minute. This capacity meets the demand of a WR 2500 stabilizing a 300 mm thick layer with 4% cement at a for ward speed of over 10 m/min.

Figure 2.12 shows the main features of the WM 1000.

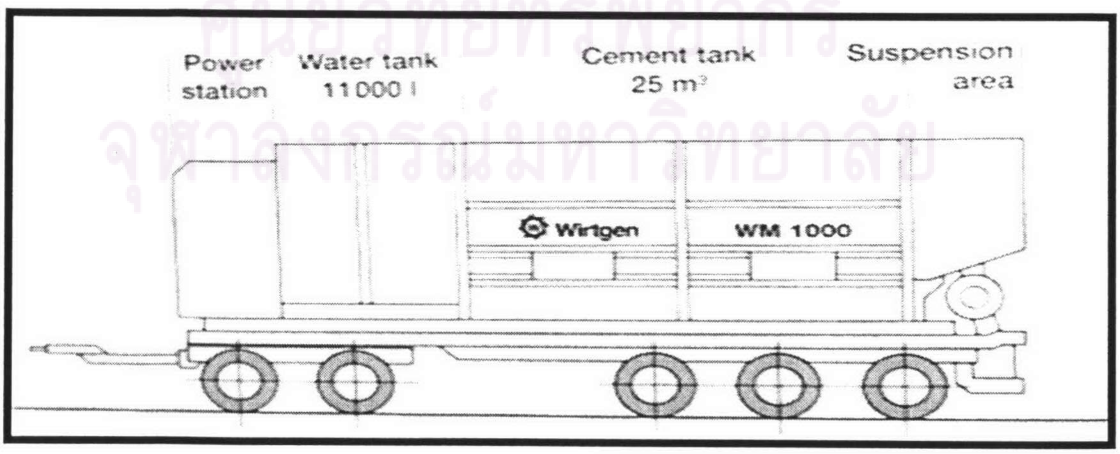

Figure 2.12 The main features of the WM 1000

Source: Wirtgen cold recycling manual 2001

2.2 Advantage of Cold-Recycling

The following advantages of foamed asphalt are well documented:

1. RAP materials can be reused with a stabilizing agents procedure and virgin aggregate to reduce budget for materials movement
2. Reduces fuel cost for heating aggregate as well as pollution during mixing
3. With an efficient machine, the quality is higher and paving and compaction are smoother and of higher density
4. Cold in-place recycling has minimal effect on road structure because the work can be completed in a single cycle
5. Work is very fast, causing minimal effect to traffic flow
6. Work area is a single lane causing minimal effect to traffic flow
7. The foamed binder increases shear strength and reduces moisture susceptibility of granular materials. The strength of foamed asphalt approaches that cement, but foamed asphalt is flexible and fatigue resistant
8. Foamed treatment can be used with a wider range of aggregate types than other cold mix processes
9. As foamed asphalt requires less binder and water than other types of cold mixing, there area reduced binder and transportation costs
10. Because foamed asphalt can be compacted immediately and carry traffic almost immediately after compaction is completed, time expenditure is more economical
11. Because only the bitumen needs to be heated while the aggregates are mixed in while cold and damp (no need for drying), energy is conserved
12. Environmental side-effects resulting from the evaporation of volatiles from the mix are avoided since curing does not result in the release of volatiles
13. Foamed asphalt can be stockpiled with no risk of binder runoff or leeching. Since foamed asphalt remains workable for extended period, the usual time constraints for achieving compaction, shaping and finishing of the layer are avoided

14. Foamed asphalt layers can be constructed in adverse weather conditions, such as in cold weather or light rain, without affecting the workability or the quality of the finished layer

2.3 Benefit of Cold Recycling

Several benefits can be realized from cold recycling, some of which are readily evident while others tend to be less tangible.

2.3.1 Environmental

Full use is made of the materials in the existing pavement. Spoil sites do not have to be found and the volume of new materials that has to be imported from quarries is minimized. This reduces scars in the county side from quarries and borrows pits. Haulage is much less. The overall energy consumption is thus significantly reduced as is the damaging effect of transport vehicles on the road net work.

2.3.2 Recycled Layer Quality

Consistent high quality mixing of the in-situ materials with water and stabilizing agents is assured. The addition of the fluids is accurate, thanks to the micro-processor controlled pumping systems. Excellent mixing take, place as the components are rigorously mixed together in the mixing chamber.

2.3.3 Structural Reliability

Cold recycling produces thickness and bound layers that are homogeneous and do not contain weak interface between thinner pavement layers, as is sometimes found in conventionally constructed pavements.

2.3.4 Sub-Grade Is Not Disturbed

Much less disturbance of poor quality sub-grade occurs, compared to pavement rehabilitation using conventional construction equipment. Cold recycling is typically a single pass operation with a recycler or high flotation types passing only once over the exposed sub-grade. The sub-grade is subjected to repeated high stress loading with conventional equipment, often resulting in conditions and necessity to excavate and the backfill with imported materials.

2.3.5 Shorter Construction Time

Modern recycling machine are capable of high production rates that significantly shorten construction times compared to alternative rehabilitation methods. The shorter construction time. This provides a largely intangible benefit for the road user as traffic is disrupted for less time on the specific project.

2.3.6 Traffic Safety

One of the most important benefits of this process is the high level of traffic safety that can be achieved. The full recycling train can be accommodated within the width of a single traffic lane. For example, on roads with two traffic lanes, recycling can be carried out along one half of the road-width during the day, and the full road width, including the completed recycled lane, reopened to traffic by nightfall.

2.3.7 Cost Effectiveness

The above benefits all combine to make cold recycling a most attractive process for pavement rehabilitation in terms of cost effectiveness.

2.4 Stabilizing Agents

Stabilizing is currently the most widely used method in the world, whether it is stabilizing with cement, foamed asphalt or emulsion asphalt. The aim is to achieve binding of particles for increased strength higher water resistance.

Stabilizing agents are very important and depend on their materials. They can be separated into cementitious stabilizing agents and bituminous stabilizing agents used in construction. Both are generally available worldwide.

2.4.1 Cementatious Stabilizing Agents

Cement is most commonly used stabilizing agent; its use worldwide for exceeds all other stabilizing agents. The main reason for this is its availability as cement is manufactured in most countries and readily available throughout the world.

The cementitious stabilizing agent lime Portland cement is suitable for a fine-grained base and sub-base because the lime forms a clay while the Portland cement increases strength. If Portland cement is only used it tends to cracked or reduce the pavements flexibility which affects fatigue resistance.

Cracking of cement is caused by:

1. 2-4% Portland cement mixture.
2. Plastic index of aggregate greater than 10 (PI>10)
3. Loose of moisture content between specimens curing.

2.4.2 Bituminous Stabilizing Agents

The bituminous stabilizing agent consists of bitumen emulsion and foamed asphalt. The bitumen treatment is a cost-effective way of improving the strength of materials and reduces the effects of water. Bitumen bound material produces a flexible layer with superior fatigue properties compared to those treated with the cementitious stabilizing agents. The problem of bitumen emulsion is its moisture during compaction.

Table 2.1 Advantages and disadvantages of cement

Advantages	Disadvantages
Availability: Cement can be obtained worldwide, either in bulk or bagged	Shrinkage cracking is unavoidable, but can be minimized
Cost: Compared to bitumen it is normally in-expansive.	Increases rigidity which reduces fatigue characteristics.
Ease of application: Cement can be spread by hand in the absence of speared and slurry mixers.	Requires proper curing. Early trafficking can damage the surface.
Acceptance: Cement is well known in the construction industry. Standard test methods and specifications are usually available.	
Significant improvement of compressive strength properties with most materials.	
Improves a material's resistance to water.	

2.2 Advantages and disadvantages of foamed bitumen

Advantages	Disadvantages
Ease of application: Like with bitumen emulsion applied through a special spray bar after coupling the bulk supply tanker.	Foaming demands that the bitumen is hot, typically 170 °C, which requires special heating facilities and safety precautions.
Flexible strong pavement: Foamed bitumen treated materials have a flexible mortar bounding with courser particles. It therefore exhibits superior resistance to both deformation and fatigue.	Bitumen quality: The qualities of stabilized materials are determined by the foaming characteristics which are predominantly dependent on the quality of the bitumen.
Cost: Foamed bitumen uses standard penetration grade bitumen. There are no manufacturing costs.	Material types and condition: Saturated materials and materials deficient in fines aggregates cannot be treated with foamed bitumen.
Rate of gain of strength: Materials may support flow immediately after installation.	

Table 2.3 Advantages and disadvantages of bitumen emulsion

Advantages	Disadvantages
Flexible pavement: Stabilizing with bitumen creates a visco-elastic material with superior fatigue properties. Ease of application: The recycler is coupled to the bulk tanker for application through a spray bar. Acceptance: Bitumen emulsions are relatively well known in the construction industry. Standard test methods and specifications are available.	Cost: Bitumen emulsions are not normally manufactured on site-process requires strict quality control. Emulsifying agents are expensive. Transporting water, not only bitumen. Moisture content of the materials in existing pavement is sometime too high and becomes saturated when the emulsion is added. Curing can take a long time. Strength development is dictated by moisture loss. Availability: The required formulation for recycling work may not obtainable.

Source: Wirtgen cold recycling manual 2001

2.5 Foamed Asphalt Characteristics

Foamed characteristics are characterized in terms of expansion ratio and half-life. The expansion ratio is defined as the ratio between the maximum volumes achieve in the foamed stated and the volume of foamed bitumen. The half-life is the time taken, in seconds, for the foamed collapse to half of the maximum volume attained

The Foamed Asphalt characteristics are specified in two parameters:

1. Expansion Ratio
2. Half-life

Expansion Ratio: Ratio of maximum volume of foamed bitumen produced relative to the original volume of the bitumen.

Half-Life: The time taken for the foamed bitumen to collapse from its maximum volume.

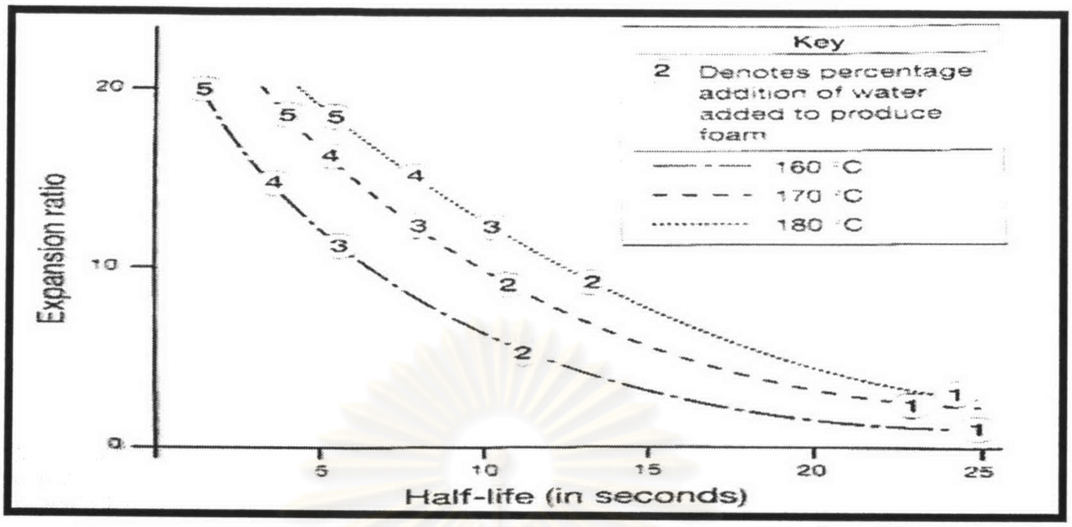

Figure 2.13 Typical foaming characteristics

Source: Wirtgen cold recycling manual 2001

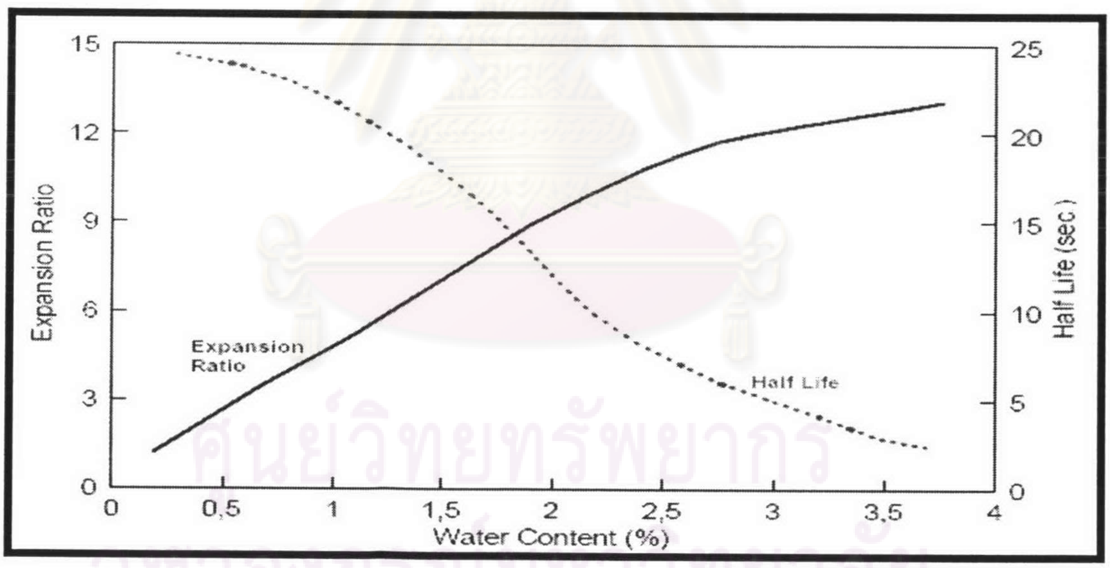

Figure 2.14 Expansion Ratio and Half-Life Relationship

Source: Martin Kendall, Jothi Ramanujam

The quantity of Foamed Asphalt increases in a surface area when small amounts of water are added to hot bitumen, significantly reducing the viscosity of the bitumen. In this form, it is well suited for mixing with cold damp aggregate.

The foaming characteristics of specific bitumen are influenced by numerous factors, the most important being:

1. Soft asphalt or low penetration value is given to high foamed qualification, Penetration smaller than 100 grade is suitable for tropical areas.
2. The foaming characteristics of most bitumen improve with higher temperatures.
3. The expansion ratio increase with an increase in the amount of water added, whilst the half-life is decreases.
4. Low pressures (be-low 3 bars) negatively affect both the expansion ratio and half-life.
5. Presence of anti-foaming agents, such as silicone compounds.

2.6 Foamed Asphalt Procedure

Adding a small amount of water or steam to hot bitumen (160 to 200 °C) results in the formation of foam that expands to many times the origin volume of the bitumen. The low viscosity of the foamed allows it to mix easily with aggregate and breaks preferentially coating of the fine aggregate in mix. After that, foamed asphalt is suitable for mixing with the cold damp aggregate. The potential of using foamed bitumen as a cold-mix binder was first realized by Prof. Ladis Csanyi at the Engineering Experiment Station of the Lowa State University in 1956 where a steam injection process was used to make foam.

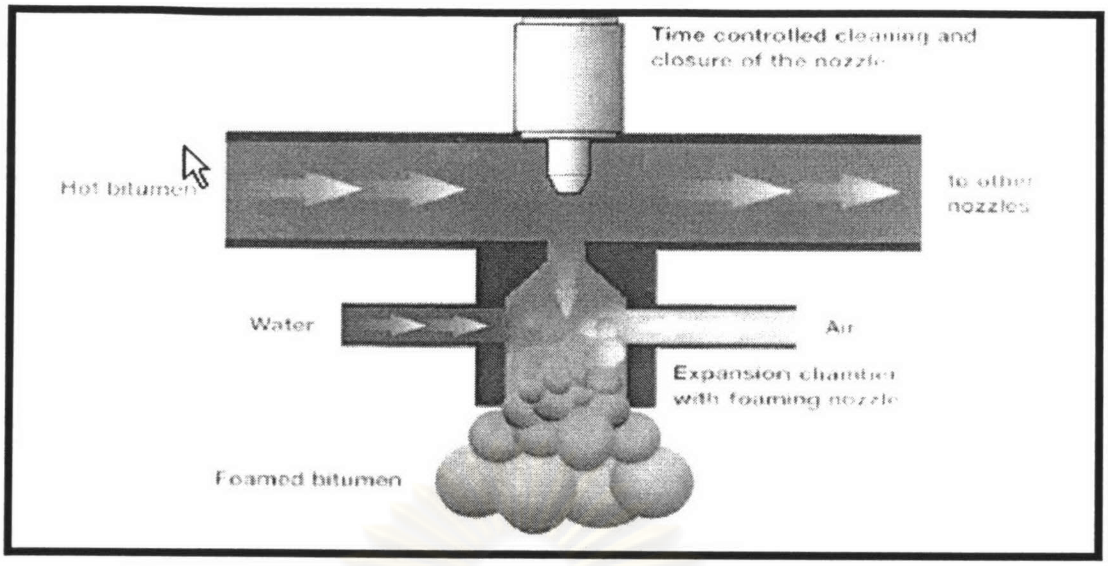

Figure 2.15 Schematic of foamed asphalt procedure

Source: Stefan A. Romanochi, Mustague Hollain

2.6.1 Bitumen Dispersion

Cold recycling, unlike hot-mix asphalt, produces a material stabilized with foamed bitumen that is not black. This is because the coarser particles of materials are not coated and are usually free of bitumen. When foamed bitumen comes into contact with materials, the bitumen bubbles burst into millions of tiny " spots that seek " out and adhere to fine particles, particularly those less than 0.075 mm. This results in a bitumen bound filler that acts as a mortar between the coarse particles. There is therefore only slight darkening in the color of the materials after treatment.

The additions of cement, lime or other such fine ground materials (100 % passing 0.075 mm sieve) are shown in Figure 2.16 and 2.17 under Materials Suitability.

The base-course materials are very important for road construction whether new natural materials or RAP. The natural or RAP materials size from course to fine is a key property of aggregate gradation affecting the workability of Portland cement or foamed or stabilized bitumen mixes. The materials should be uniform or within assigned specification, the percentage passing of No 200 (0.075 mm) at least 5% and the base course may also include several types of under course, such as sub-base, leveling course.

2.7 Materials Suitability

2.7.1 Foamed Asphalt Materials

Figure 2.16 shows typical material suitabilities. The materials that are not fine will not mix well with foamed bitumen. The minimum requirement is 5 % passing through a No 200 (0.075 mm) sieve. When materials are enough, the foamed bitumen dose not disperses properly and tends to form what is known as "stringers", or bitumen-rich agglomerations throughout the recycled material. These stringers vary in size according to fineness deficiency. A large deficiency will result in many large stringers which will tend to act as a lubricant in the mix and lead to a reduction in strength and stability.

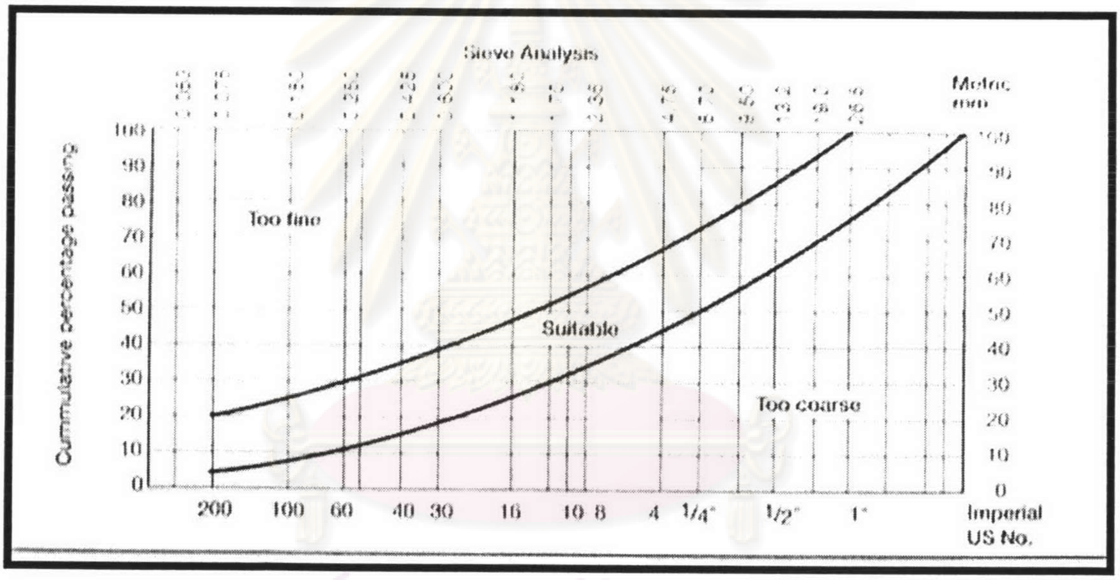

Figure 2.16 Materials suitability

Source: Wirtgen cold recycling manual 2001

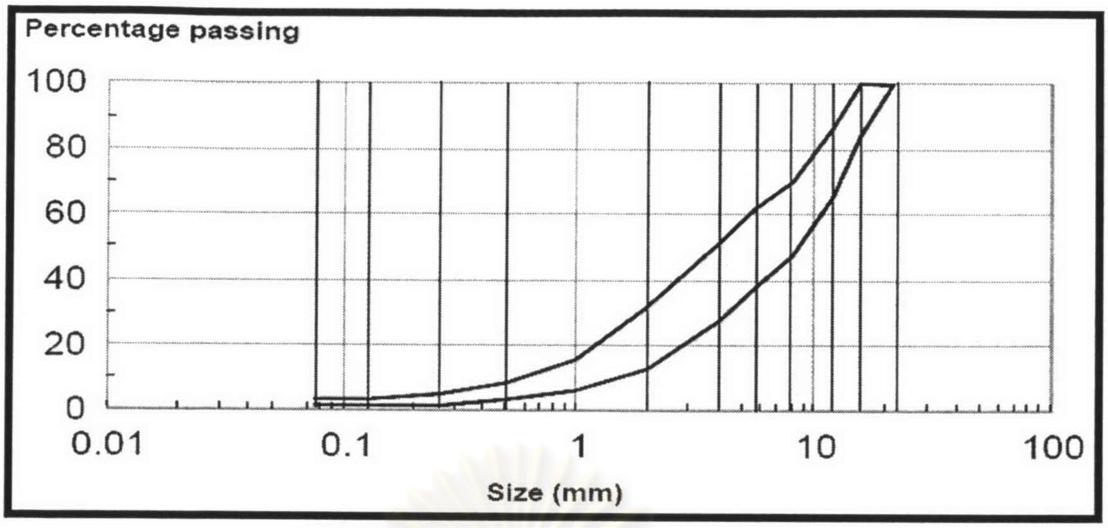

Figure 2.17 Suggestions of gradations

Source: Gunnar Hillgren, Alan James Tomas Svenson and Thomas Wallin, Sweden. 1996

Figure 2.17 shows In-plant cold recycling and cold mix development in Sweden - during Laboratory Testing. The conclusion is that the residual binder on the old RAP should not be more viscous than 30 pen and have up to 15% virgin aggregate. Typically 8 mm course sand can be added to correct the grading.

2.7.2 Portland Cement Materials

Materials for stabilized Portland cement were determined by AASHTO T 27. The RAP materials as well as the foamed bitumen materials should be uniform or within range specification passing No 200 (0.075 mm) sieve, at least 5% by weight. Figure 2.18 shows typical range gradation materials. The maximum particle size is less than ¾ in. (19 mm).

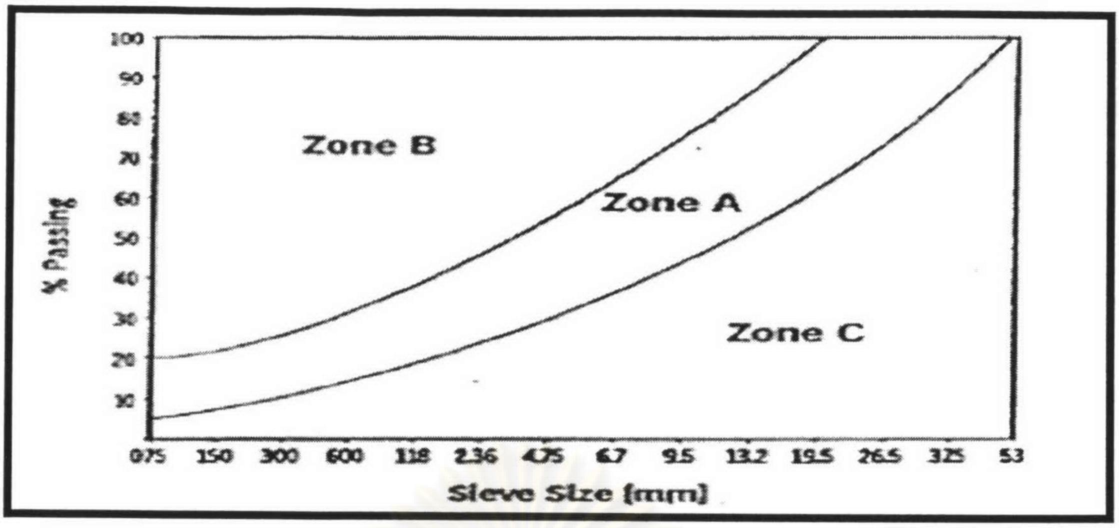

Figure 2.18 Gradation ranging

Source: Gunnar Hillgren, Alan James Tomas Svenson and Thomas Wallin, Sweden. 1996

2.8 Criteria for Stabilized Foamed Asphalt

Specification for foamed asphalt mixture in engineering is very important to specify the efficiency in real work. The best materials of a foamed asphalt mixture depend on mixing duration. To find the optimum content, the RAP and virgin aggregate blends differ according foamed asphalt content, as shown in Table 2.4.

Table 2.4 Bitumen range of foamed asphalt mixture

RAP/Crushed stone (50/50 Blend)	1.5 to 3.0 % (By mass)
Crushed stone	2.5 to 4.0 % (By mass)
Natural Gravel PI <10, CBR>30	3.0 to 4.5 % (By mass)

Bitumen stabilized material strength is normally evaluated using the Indirection Tensile Strength (ITS) in preference to Superpave testing. The test is conducted on standard Superpave briquette specimens at one temperature, only 25°C, and the following range of ITS values are typical.

Table 2.5 Indirect Tensile Strength (ITS) of Foamed Asphalt Mixture

RAP/Crushed stone (50/50 Blend)	359 to 800 kPa
Crushed stone	400 to 900 kPa
Natural Gravel PI <10, CBR>30	250 to 500 kPa

The residual modulus (M_R) of bitumen stabilized material is measured by subjecting a specimen to repeated load testing. Typical values are:

Table 2.6 Resilient Modulus (M_R) of Foamed Asphalt Mixture

RAP/Crushed stone (50/50 Blend)	2500 to 5000 MPa
Crushed stone	3000 to 6000 MPa
Natural Gravel PI <10, CBR>30	2000 to 4000 MPa

2.9 Criteria for Cement Stabilized

The most important engineering property applicable to cement stabilized materials is strength. The strength or unconfined compressive strength (UCS) test is the most commonly used test for evaluating cement materials since the CBR is not considered to be sufficiently sensitive for testing high-strength materials.

UCS test is normally conducted on prepared specimens that have cured for 7 days at temperatures of 22 -25°C and humidity of over 95%.

Cement contents that result in an UCS value between 1.5 to 3.0 MPa are normally the target for recycled materials in the upper portion of a pavement, stated as a percentage by mass of the recycled materials.

Table 2.7 Cement Range of Portland Cement Mixture

RAP/Crushed stone (50/50 Blend)	1.5 to 3.0 % (By mass)
Crushed stone	2.5 to 4.0 % (By mass)
Natural Gravel PI <10, CBR>30	3.0 to 4.5 % (By mass)

Table 2.8 Indirection Tensile Strength (ITS) of Portland Cement Mixture

RAP/Crushed stone (50/50 Blend)	n/a
Crushed stone	n/a
Natural Gravel PI <10, CBR>30	n/a

The Residual modulus (M_R) of cement stabilized material is measured by subjecting a specimen to repeated load testing. Typical values are

Table 2.9 Resilient Modulus (M_R) of Portland cement Mixture

RAP/Crushed stone (50/50 Blend)	~ 5000 MPa
Crushed stone	~ 5000 MPa
Natural Gravel PI <10, CBR>30	~ 4000 MPa

2.10 Literature Review

Mofresh Saleh (2001) said that foamed bitumen stabilization of base course materials offers the advantages of reduced transverse shrinkage cracking and a fast stabilization process with minimum traffic delays. He further stated that the performance of foamed stabilized aggregates is comparable with or better than that of bitumen emulsion stabilized materials.

Stefan A (2003) said that the optimum water content for foaming was found to be 3% water injection rate at a binder temperature of 160 Celsius (320 °F). The added asphalt cement at which the soaked indirect tensile strength of the mixture was maximum with a 3% water injection rate at a temperature of 160 °C with materials classified as AB-3 by current KDOT. The optimum moisture content was 10% for granular base and compaction was done using the Vibratory plate compactor very high density.

Etsuo Sekine, chief research engineer, and partners said that vacavic-cohesive –clay chemical stabilized soil with a static strength five times or over the repeated load shows only small plastic settlement and is highly durable.

Ibrahim M (2001) said that stabilization dune sand in foamed asphalt had an optimum asphalt content of 7% for foamed asphalt content mixes, the resilient modulus (M_R), (ASTM D4123) value and dynamic loading of 1.0 Hz was found to be M_R = 1750 MPa. For emulsion asphalt (EA) two types of mixes were evaluated with and without the addition of 2% Portland cement, asphalt cement at maximum soaked stability of emulsion asphalt mixes was 4.9 KN. With 5% emulsion, 5.7% content asphalt content, the value of resilient modulus (M_R) was found to be 1500 MPa, which is some what less than that of the optimum foamed asphalt content mix with 1745 MPa.

Ramzi Taha (2002) talked about the cement stabilization of reclaimed asphalt pavement aggregate for road base and sub-base. Five blends of RAP and virgin aggregate were 100%, 90%, 80%, 70% and 0%, respectively and using 0%, 3%, 5%, and 7%. Type I Portland cement, curing at 3, 7, and 28 days in plastic bags at room temperature, results indicate that the OMC, MDD and RAP strength will generally increase with the addition of virgin aggregate and cement. Longer periods will yield higher strength.

S.A. Shihata (2001) said that the PCA suggested three cement contents of 5%, 7% and 9% by mass durability test. The standard proctor compaction test using 7% cement resulted in the following values of maximum dry density (MDD) and the corresponding optimum moisture content (OMC), which had been used in specimen preparation.

PCA (1992) minimum residual strength of un-brushed soil cement = 6.2 MPa, and 11% acceptable mass loss masses are required by the US Army Corps of engineers while at 14% the residual strength = 5.8 MPa, compressive strength = 3.2 MPa with 11% cement and =3.0 MPa with 14% cement.

Dr. Teeracharti Ruenkrairergsa of the Thai Highway Department. Said the advantages disadvantages of cold deep in-place recycling is the construction of cement/asphalt recycled base increases the strength of road structure by cement/asphalt addition into the surface.

Ruckel (1983) recommend limits of 8-15 for the expansion ratio and at least 20 seconds for the half-life.

Maccarrone (1995) using certain surface-active additives it is possible to produce highly expanded and stable foamed bitumens with expansion ratios greater than 15 and half-life greater than 60 seconds

Brennen (1980) found that the half-life and expansion ratio of the foamed produced from any particular bitumen was affected by the volume of foamed, the quantity of water and the temperature at which the foamed was produced. Higher foaming temperatures and increased quantities of water both resulted in increased expansion ratios, but resulted in decreased half-life.

Lee (1981) found that the optimum mixing moisture content occurs in the range of 65 - 85 percent of the modified AASHTO OMC for the aggregates. This optimum range of moisture contents for mixing was confirmed by Bissada (1987).

Ruckel et al (1982) concluded that the moisture content during the curing period had a major effect on the ultimate strength of the mix.
Lee (1980) provided experimental evidence which suggested that moisture loss was not a prerequisite for strength gain in foamed asphalt mixes.

Castedo Franco et al (1984) found that additives such as lime reduced the moisture susceptibility of the mixes. Cement was also found to be as effective as lime, and cheaper (Lewis, 1998). Higher bitumen contents also reduce moisture susceptibility because higher densities are achievable, leading to lower perm abilities (lower void contents), and to increased coating of the moisture-sensitive fines with binder.

Maccarone (1997) the stiffness of foamed asphalt depends on the loading rate, stress level, and temperature. Generally stiffness has been shown to increase as fine content increases. Strength of foamed asphalt mixtures depends to a large extent on the density of a compacted mix. Foamed asphalt samples should be subjected to an accelerated curing procedure before undergoing any test.

Recommended foamed bitumen gravel cured for 3 days at 60°C find out

Dry-ITS at least 200 kPa

Wet-ITS at least 100 kPa.

Lanster (1994) suggested that the resilient modulus of foamed asphalt mix is at least 1500 MPa and 6000 MPa for soaked and dry sample respectively. As recommended dynamic creep testing to evaluate the permanent deformation of foamed asphalt mixes minimum dynamic creep modulus of 20 MPa.

Best practice guide (2002) the temperature of foamed asphalt before foaming should be in the range of 180-200°C. it is recommended the half-life of foamed bitumen be at least 12 seconds and expansion ratio be at least 10:1

Retain ITS at 25°C = 60%

Min. Dry-ITS = 100 kPa – 150 kPa

Resilient Modulus = 900 MPa – 1500 MPa

Dynamic Creep = 10 MPa-15 MPa

Rajib B. Mallick (2004) reported that the foamed asphalt mix included 75% ash and 25% recycled concrete with 4%bfoamed asphalt content a mean ITS dry of 208 kPa, with ITS wet of 95 kPa and retained ITS of 46%.

2.11 Flowcharts

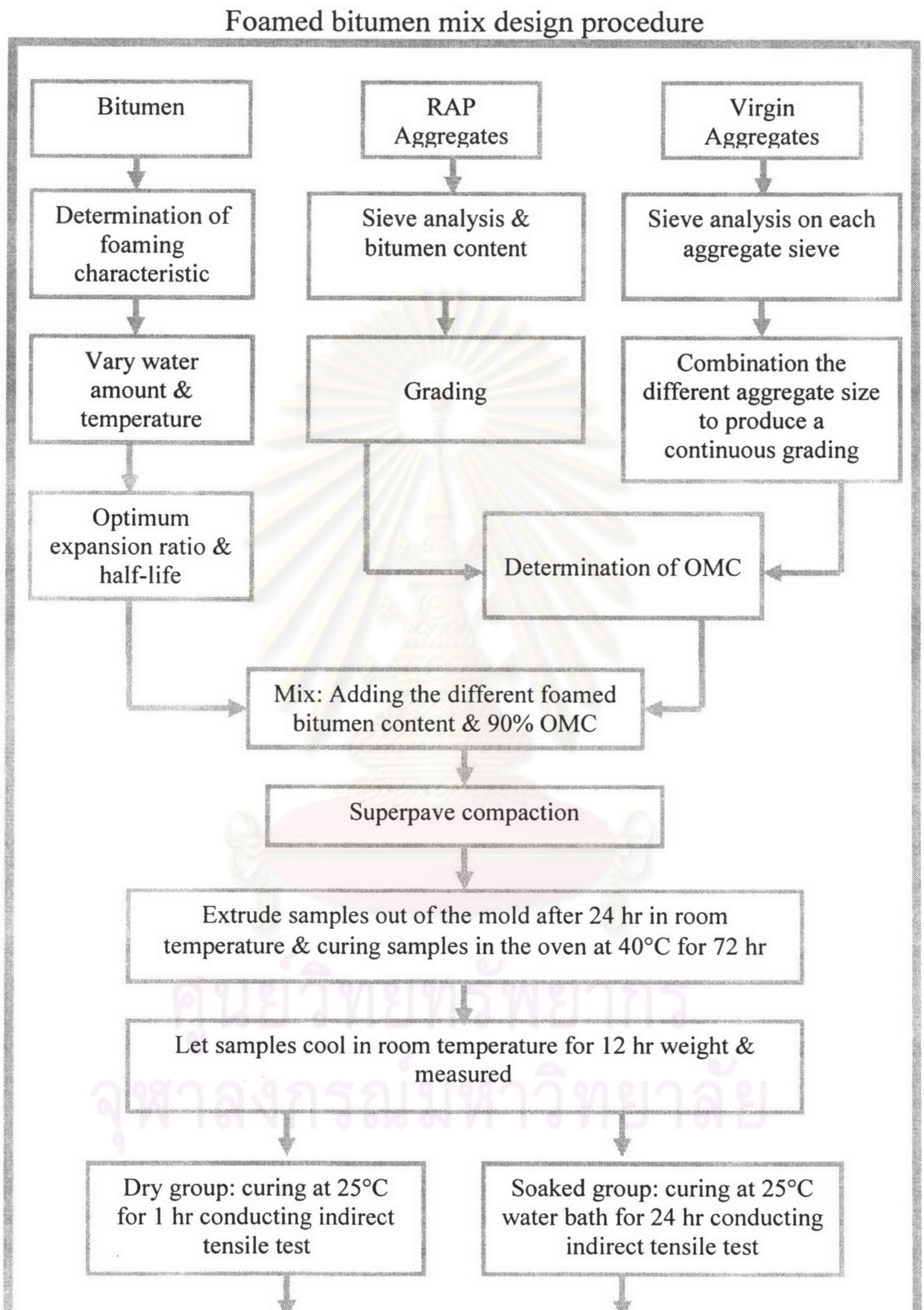

Figure 2.19 Procedure for foamed bitumen mix design

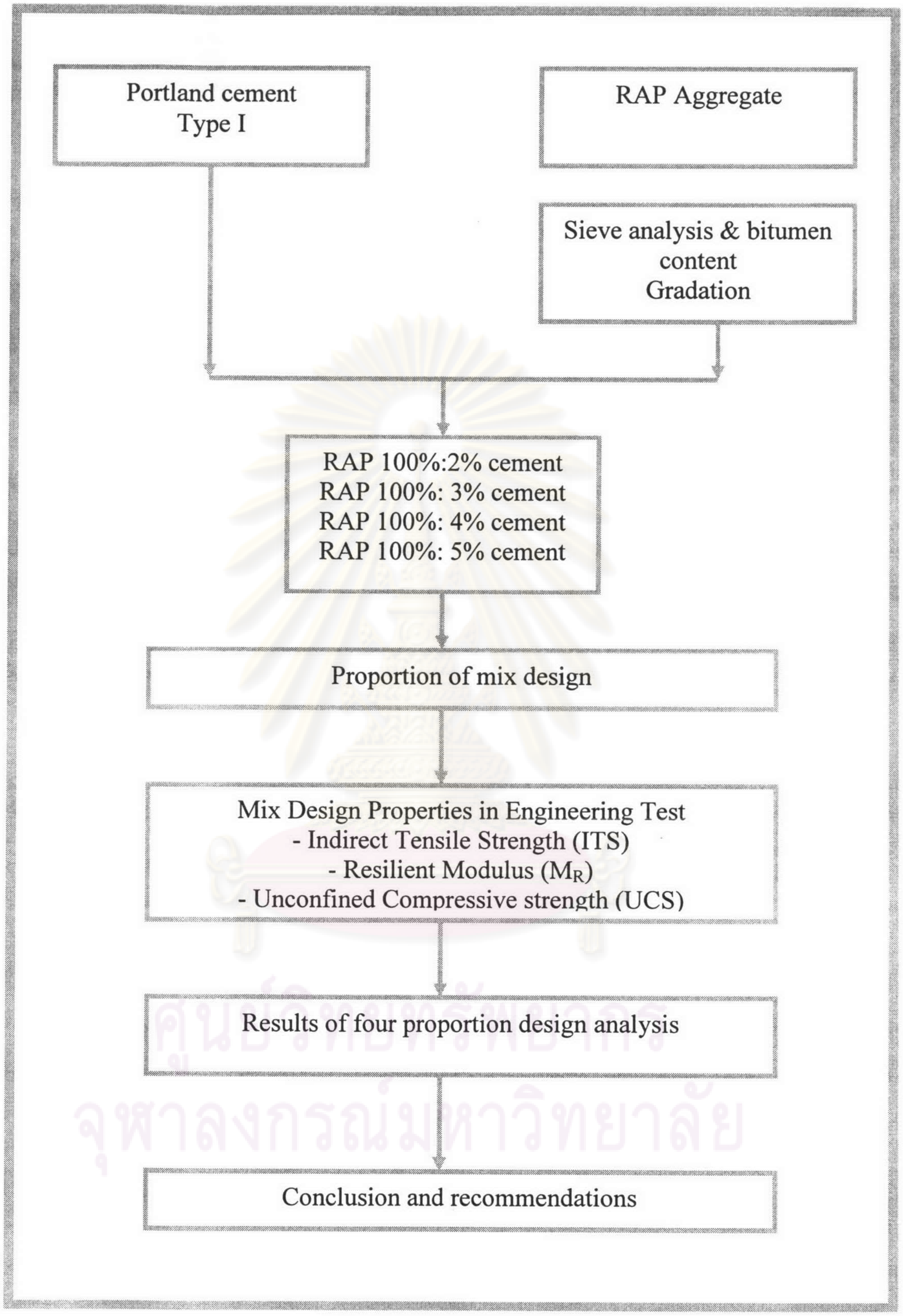

Figure 2.20 Procedure for portland cement mix design