Chapter

Recycling Asphalt Pavements: The State of Practice

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Abstract

Millions of miles of paved roads in the world need rehab, maintenance, and upkeep. To sustain this effort, pavement engineers are challenged to find innovative ways to maintain the roads in an economical and environmentally responsible fashion. Pavement recycling is a clear way to achieve sustainability. This chapter provides a brief introduction and outlines the state of practice with respect to asphalt pavement recycling. The reuse of various pavement layers (asphalt, asphaltic base, granular base, and subbase) is discussed. The ways of utilizing the material, from the highest to the lowest economical use, are presented. The methods of recycling individual layers or combining multiple layers are discussed.

Keywords: reclaimed asphalt pavement, recycling asphalt, rejuvenator, base course, subbase, embankment, emulsion, foamed asphalt, full depth reclamation

1. Introduction

Removed pavement material through the process of reconstruction or resurfacing work is known as Reclaimed Asphalt Pavement (RAP). It is recognized to contain usable aggregate and asphalt binder. Historically, asphalt mix with RAP began in 1915. Its usage is increasing since the rise in oil prices happened in 1970s. RAP became an attractive option to reduce economic cost of roadway construction. This is due to decreasing demand for asphalt binders. State DOTs used RAP for many years before the beginning of Superpave era in the late 1990s. The maximum quantity of RAP is found in surface layer. In the US, the average RAP content in asphalt mixture is 12–15% for a new construction project [1]. RAP application now is accepted all over the world [2]. Denmark, France, Sweden, and Germany were found to be the significant RAP users in Europe. In addition to these four countries, the Netherlands uses 30–40% proportion of old asphalt for the new mixture [2]. Recently, pavement research community is working on advancing RAP usage practice by raising RAP content to 40-50% and up to 100% [3].

Roadways in the US comprise more than 90% built with asphalt layer. The pressure needs to maintain the performance and rehabilitate an aging asphalt is growing and will continue to occur. The same material used to construct the roadway can be reused to prolong pavement life cycle. RAP usage will be projected to be more common as RAP offers more environmental benefits than virgin material. A primary activity of pavement maintenance is milling operation. Milling process produced RAP that consists of aged asphalt binder and original aggregates. RAP usage is aligned with global Sustainable Development goals because of provident use of natural resources. RAP application promotes natural resource preservation and reduces landfill occupation from disposal of roadway construction and maintenance projects. Energy consumption will also be reduced since there will be less transportation demand for virgin material from site plant or material disposal to landfill site. In 2017, 76.2 million tons of RAP were recycled in the US and it is increased to 89.2 million tons in 2019 [4]. In EAPA's (European Asphalt Pavement Association) report released in 2020, 50 million tons or RAP were recycled in all European Union countries [5]. The report from 2016 showed RAP usage for over 60 million tons in China [6].

Economic savings have been highlighted by numerous literatures through different type of analysis [7–10]. Silva et al. [10] reported cost savings of $300 million when hot mix asphalt contained 30 million tons of RAP. RAP usage positively impacts the environment as RAP application reduces waste and the inherent issues around the disposal of highway materials [11, 12]. A cost saving from $6.80 to $3.40 per ton will be generated when a mixture contain RAP from 15% to 40% [13]. A predicted reduction of energy consumption from 16% to 25% for a mixture that uses 16% to 25% RAP [14].

One of the significant value-added measures available to highway agencies is increasing the application of RAP in the construction and rehabilitation of asphalt pavements. RAP used in new pavement mixtures replaces a portion of the expensive virgin binder and virgin aggregate and provides protection from the volatility of asphalt binder price variability. The cost to prepare RAP for use in new mixtures is consistent. The value of the RAP is essentially the cost per ton of virgin mix (i.e., value of the virgin aggregate and virgin asphalt) minus the cost to acquire and process the material for use in new mixtures. It is suggested a mix with 30% RAP has equivalent performance to a mix with all virgin material [15].

Experiment with Hamburg Wheel tracking test that a mixture with 30% and 50% combined with a soft binder showed similar performance with virgin aggregate mixture [16]. The aged, stiff binder can be compensated by the application of rejuvenating agents, softer virgin binder grade, and therefore produce acceptable pavement performance [3].

Although high RAP content is theoretically possible, advanced processing of RAP is required to make high content of RAP produce acceptable performance. Advance RAP processing like warm asphalt technology and testing will increase project costs. For this reason, advanced processing could inhibit the potential growth of high RAP content.

Highway agencies in the US have specifications for RAP application and most of them limit the amount of RAP used in specific asphalt or mixture types. In a 2009 survey conducted on behalf of the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO), one of the major concerns cited by State Highway Agencies (SHAs) regarding limited RAP application is the quality of the blended virgin and RAP binder qualities. For a high RAP mixture, the quality concern is even more emphasized.According to AASHTO M 323, the assumption which is placed to formulate current binder selection guidelines for RAP mixtures is that the virgin and RAP binders are blended effectively. Based on these guidelines, some State highway agencies give full credit to the contribution of the RAP binder to the asphalt content, which may result in an under-asphalted mixture if complete or significant blending is not occurring. A survey conducted in the US by NCHRP Synthesis 495 indicated that 100% of the RAP binder was available in the mix from 77% of all respondents. However, the study found only 42% of all respondents consider 100% of the RAS binder available in the new mix [17]. The past studies showed that the virgin and RAP binder blending amount is in the middle of complete blending and no blending (i.e., the RAP aggregate behaves like a black rock). However, there is no consensus on how to accurately determine the amount of blending with a direct method.

RAP was utilized for multiple purposes in pavement engineering, from asphalt concrete, to unbound granular layer, to embankment fill. Asphalt binder is the costliest component in the asphalt mixture. As the aged asphalt contained in RAP reduces the needed binder for the new mix; therefore, the most valuable usage of RAP is in asphalt mixtures. Similar performance of road section containing at least 30% asphalt performs similarly to virgin section [18].

A summary of reclaimed material usage in pavement engineering is summarized in **Table 1** [19, 20].

2. Recycling the asphalt concrete layer

This section describes the recycling of the asphalt layer alone. Despite the various application of RAP content in pavement asphalt layers, there is an increasing trend on application of a high RAP proportion in the new mixture [21]. Moreover, Perez and Maicelo [21] discussed from various literature the performance, fatigue life, rutting, and cracking of RAP with different proportions and mixing techniques in asphalt mixtures.

Naulkha [22] summarized the mechanical properties and performances of RAP. RAP creates a rut and skid-resistant layer due to an aggregate interlocking effect. Air voids are reduced with more RAP in the mixture.

Asphalt recycling methods are classified based on treatment place, temperature treatment, characteristic material, type of binder, etc. In general, there are five categories of asphalt recycling, and these methods can be combined one with another [23]:

Cold Planning: Cold planning (milling) uses specific equipment to remove asphalt layer into specified depth, longitudinal profile, and cross-slope.

Hot Recycling: A process to produce recycled mix from the combination of RAP with virgin aggregate, new binder, and rejuvenating agents, as needed to be conducted in central plant.

Hot In-Place Recycling: The process consists of heating and softening the existing asphalt, milling it to a specified depth, and then mixing and placing it with conventional paving equipment. All recycling processes are done on-site. Treatment depths range from ¾, 2, and 3 inches. Hot in-place recycling subcategories are Surface Recycling (Resurfacing), Remixing, and Repaving.

Cold Recycling: Asphalt recycling process without heat application. Cold recycling can be done in-place and in-plant.

Full Depth Reclamation: Full thickness of asphalt layer and predetermined underlying materials is pulverized, blended, and then stabilized using various methods like mechanical stabilization, binder-based stabilization, and chemical stabilization.

Application/use	Material
Asphalt Concrete—Aggregate (Hot Mix Asphalt)	Blast Furnace Slag Coal Bottom Ash Coal Boiler Slag Foundry Sand Mineral Processing Wastes Municipal Solid Waste Combustor Ash Nonferrous Slags Reclaimed Asphalt Pavement Roofing Shingle Scrap Scrap Tires Steel Slag Waste Glass
Asphalt concrete—aggregate (cold mix asphalt)	Coal bottom ash Reclaimed asphalt pavement Blast-furnace
Asphalt concrete—aggregate (seal coat or surface treatment)	Blast-furnace slag Coal boiler slag Steel slag
Asphalt concrete—mineral filler	Baghouse dust Sludge ash Cement kiln dust Lime kiln dust Coal fly ash
Asphalt concrete—asphalt cement modifier	Roofing shingle scrap Scrap tires
Portland cement concrete—aggregate	Reclaimed concrete
Portland cement concrete—supplementary cementitious materials	Coal fly ash Blast-furnace slag
Granular base	Blast-furnace slag Coal bottom ash Coal boiler slag Mineral processing wastes Municipal solid waste Combustor ash Nonferrous slags Reclaimed asphalt pavement Reclaimed concrete Steel slag Waste glass
Embankment or fill	Coal fly ash Mineral processing wastes Nonferrous slags Reclaimed asphalt pavement Reclaimed concrete Scrap tires
Stabilized base—aggregate	Coal bottom ash Coal boiler slag
Stabilized base—cementitious materials (Pozzolan, pozzolan activator, or self-cementing material)	Coal fly ash Cement kiln dust Lime kiln dust Sulfate wastes
Flowable fill—aggregate Flowable	Coal fly ash Foundry sand Quarry fine

Application/use	Material
Flowable fill—cementitious material (pozzolan, pozzolan activator, or self-cementing material)	Coal fly ash Cement kiln dust Lime kiln dust

Table 1.
Recycled materials usage in pavement construction [19, 20].

2.1 Milling and reuse of RAP

Milling and full depth removal are the primary processes of asphalt pavement removal found in maintenance and rehabilitation project. In a single pass, up to a 2-in surface layer can be removed by a milling machine. Meanwhile, a full depth removal uses pneumatic pavement breakers to rip and break the pavement. The process will continue by pooling the removed material to a haul-trucks with a front-end loader and transporting the material to asphalt plant processing facility or use in place processing equipment. The RAP will be crushed, screened, and conveyed.

The most common RAP processing activity is conducted in central processing plants where a self-propelled pulverizing machine is used to pulverize RAP materials. The process includes mixing with stabilized base courses or granular material. Recent practice in hot in-place and cold in-place paving operations involves continuous train operations of partial depth removal, mixing RAP with virgin aggregate, binder, rejuvenating agents, and then placing and compacting in one pass.

2.1.1 Use of RAP in plant produced HMA (highest economic value)

In-plant production HMA consists of mixing of new materials with RAP to produce hot mix asphalt. Recycling agents are utilized to improve the chemical composition, rheology, and dispersion of aged bitumen contained in RAP. Adding a recycling agent is proven to produce a comparable performance to a virgin binder. According to ASTM D4552 "Standard Practice for Classifying Hot-Mix Recycling Agents", recycling agents are categorized mainly into three, namely: asphalt cements, naphthenic aromatic oils, and paraffin oils. The dose of a rejuvenating agent for RAP can be specified by ASTM D4887 "Standard Practice for Preparation of Viscosity Blends for Hot Recycled Bituminous Materials". Absolute viscosity and performance properties are target parameters for asphalt mixes with RAP. Recycling agent's critical parameters in their physical and chemical properties play a controlling factor in the selection of recycling agents [24]. The primary functions of rejuvenating agents are to increase maltene fractions and to decrease asphaltene. However, there is no guarantee that the durability of restored aged asphalt will increase with high restoration capacity. RAP mixes with an appropriate composition have been shown to equal and even surpass the virgin material performance.

Several works have been conducted in the past to investigate mixture performance with RAP as summarized in [25]. The stiffness of the mixes will be increased with higher RAP contents. When a soft binder is used with RAP content of 0 to 30%, a very less significant effect was found [26]. Tarsi et al. [25] also showed from their review that lower resistance to fatigue of the mixes was found when the mix used higher RAP contents [17, 27–29]. Meanwhile, different results showed higher RAP contents lead to higher rutting resistance [10, 17, 27, 30]. The mix that is not stabilized with rejuvenating agents but has higher RAP content showed higher stiffness, and the RAP mix stabilized by a rejuvenating agent performed the best fatigue resistance [10]. Zaumanis et al. [31] found all RAP mixes have similar stiffness with virgin mix. Lee et al. [32] showed no noticeable disparity in mixes with different RAP content. In the moisture damage test, several RAP mixes failed to comply with the standard criteria; on the other hand, a better moisture resistance than virgin material was shown by RAP mixes [25].

2.1.2 Use of RAP as a base material (2nd highest)

Base and the lower subbase layer are typically found underneath the asphalt layer. These lower layers have the function to reduce and spread loads within the subgrade. As a foundation for overall layers, the quality of base and subbase layer is significant to pavement service life. Subbase materials are typically coarser-grained than the granular base. Both materials are intended to offer the pavement structure's requisite bearing capacity and drainage. They are necessary for the longevity of pavement performance.

A resilient modulus measurement from field and laboratory showed that RAP application for base and subbase layer exhibited equivalent strength to dense graded aggregate [19]. Another study used RAP and virgin material blend with various percentages of total weight mixed aggregate which resulted in a comparable performance to the virgin base material [27].

Collins [28], an NCHRP Synthesis of Highway Practice identified an application of RAP for the unbound base and subbase layer with grading identified as the limiting factor for use. RAP used in base materials is found in 13 states, RAP used in subbase material in four states, and two states reported to use RAP application as stabilized base and shoulder aggregate [28]. The overall performance of RAP contained base and subbase layer has been identified from satisfactory to excellent. 16 state DOTs permit the use of 100% RAP as an aggregate unbound layer and five state DOTs limit it to 50% or less [30]. Potential cost benefit when RAP is used as an unbound layer with a 50% blend with virgin aggregate is approximately 30% [30].

An example of testing application for coarse aggregate is Micro-Deval test loss. Hoppe et al. [30] highlighted a test for Virginia typical coarse aggregates [33]. A test loss result of less than 15% were suitable for all applications including HMA layer with a more stringent bound layer requirement. In Ontario, Canada, a Micro-Deval test loss limits is specified as 21% for open-graded aggregate, and 30% for subbase material [33]. It is worth to mention that Ontario has high moisture effect than Virginia. Therefore, the Micro-Deval test can be applied for testing RAP application for the unbound layer.

The physical properties of RAP were found similar to crushed limestone. Hoppe et al. [30] also highlighted the gradation parameter of RAP material. RAP material has an equivalent gradation with crushed virgin aggregate. However, milling and stockpiling activities play an important role that may determine the proportion of fines in RAP, which typically, can be a large range [30]. Particles of original coarse aggregate are assumed to be strong and resistant to deformation. In contrast, accumulations of fine aggregate and asphalt mastic may be fragile or flexible. This flexibility is related to the asphalt condition like age, oxidation, and temperature [30].

Different findings on stiffness parameter in RAP specimens have been reported. Several studies have demonstrated that RAP has a relatively high modulus of elasticity, accompanied by considerable permanent deformations. In a comparison between 100% RAP specimens with dense graded aggregate, RAP specimens exhibit higher stiffness, resilient modulus value but lower shear strength. 100% of RAP specimens showed largest permanent strain regardless of high resilient modulus value. When load applies to asphalt binder, it will cause progressive decomposition of the binder and may be the cause of the significant permanent strain [34]. RAP specimens tested as unbound aggregates showed high resilient modulus and larger permanent deformation. Unbound RAP mixture also showed temperature and viscous properties dependent [33]. When RAP increases, shear strength decrease and results in lower bearing capacity compared with virgin aggregate [35, 36].

Another work reported decreasing CBR value when using RAP in the subbase layer. Under loading application, RAP aggregate slides one to another [30]. RAP contained granular mixture showed noticeable amount of creep [37]. Cosentino et al. [33] suggested a minimum 75% standard aggregate mix with an non stabilized RAP for base layer application. It is also found that 25% granular RAP and 75% of limerock satisfy base layer requirement without stabilizing agent and 50% granular RAP with stabilizing agent [38].

Meanwhile, 100% RAP is not recommended as this will not produce acceptable base performance [33, 39]. This is due to decreasing shear strength as increasing RAP content. It is recommended that only 25% of RAP content mixed with virgin aggregate and it has to be conducted in the mixing plant [40]. It is found that onsite blending has unsatisfactory performance [39].

In Florida, it is reported from a field experiment with 100% RAP in the base layer showed acceptable performance, equivalent to base layer of limerock. It is recommended to use 0.12 to 0.15 for structural coefficient for use with AASHTO empirical equation and limerock bearing ratio test is not suitable for RAP aggregate [41].

To characterize the field performance of RAP mixtures, the following tests were found to produce statistically significant performance indicators of recycled aggregates in unbound pavement layers [42]:

- Screening tests for sieve analysis and the moisture-density relationship;
- Micro-Deval for toughness;
- Resilient modulus for stiffness;
- Static triaxial and repeated load at optimum moisture content and saturated condition for shear strength; and
- Frost susceptibility (tube suction).

2.1.3 Use of RAP in embankment (lowest economic value)

Stockpiled RAP material can be used as a fill for embankment and backfill construction and as a practical alternative to stockpiled materials [38]. In this case, RAP materials are treated as granular fill. RAP material may be mixed with soil and/or fine graded aggregate when used as fill material or embankment. This option is most suitable when there is a market for reuse products or when RAP is not usable in asphalt concrete layer. FHWA reported that there are at least nine state DOTs that allow RAP material to be used as embankment or fill material. These include Connecticut, Indiana, New York, Tennessee, Kansas, California, Illinois, and Louisiana. RAP material performance for embankment or fill material is considered satisfactory and good [43]. RAP material for embankment requires minimal processing like primary crushing. A study in Wisconsin investigated the construction of embankments containing bituminous materials. The study recommended that construction should be conducted during summer to generate thermal preloading and reduce long-term settlement [40].

2.1.4 Use of RAP in pavement-preservation treatments

RAP uses in preservation treatments like micro surfacing, and cheap seals are gaining more popularity for a variety of reasons, similar performance to virgin materials, cost saving, and reduced environmental impact.

In California, despite increases in permitted RAP percentages in flexible pavement construction in California, there is still an overabundance of RAP in metropolitan areas. To cost-effectively employ recycled materials and reduce otherwise rising RAP stockpiles, agencies turned to chip sealing, slurry sealing, and microsurfacing [44].

Reclaimed asphalt pavement aggregate using polymer-modified emulsion is reported to perform well. A chip seal containing RAP and PG 76-22 rubber modified asphalt binder also performs positively. RAP slurry is widely used in Southern California [44]. RAP aggregate has lower absorption for emulsion than the virgin aggregate. RAP aggregate has also captured the emulsion instead of forming a mechanical bond as in a combination of virgin aggregate and polymer-modified slurry. In conclusion, the agencies in California will improve the specifications, particularly in treatment constructability, and increase economic and environmental benefits over the next few years based on performance evaluation.

A series of tests were conducted to compare a chip seal performance with RAP and virgin aggregate. Summary of the results is as follows:

Lifecycle cost analysis showed that a cheap seal with RAP cost lesser, around 23–37%, than a cheap seal with virgin aggregate but exhibits similar performance [45].

- Sand patch test: The mean texture depth was higher than chip seals with virgin aggregate.
- Skid resistance test: No significant difference between cheap seal with RAP and virgin aggregate.
- Direct shear test: No significant difference between cheap seal with RAP and virgin aggregate.

2.2 In-place recycling of asphalt layer

In-place recycling is gaining a position as a preferred method due to the demand for rehabilitation of old pavements exceeding the development of new roads. The attractiveness of in-place recycles is also caused by its ability to address backlog in pavement rehabilitation [46].

The cold in-place process utilizes a "train" of equipment such as tanker trucks, milling machines, crushing, and screening, mixers, pavers, and rollers. The common method of recycling HMA pavement is to grind the top layer of the old

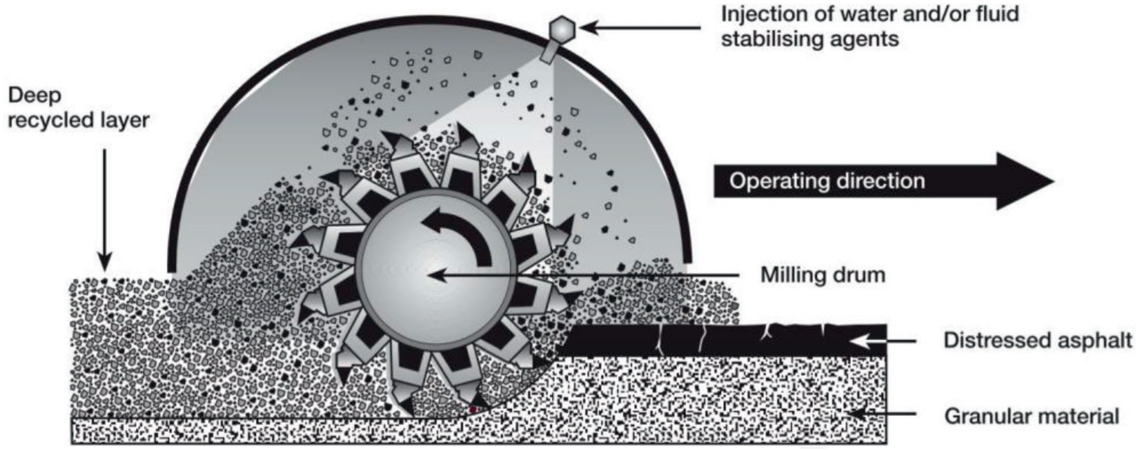

Figure 1.
Process inside the milling machine for typical cold in place recycling [46].

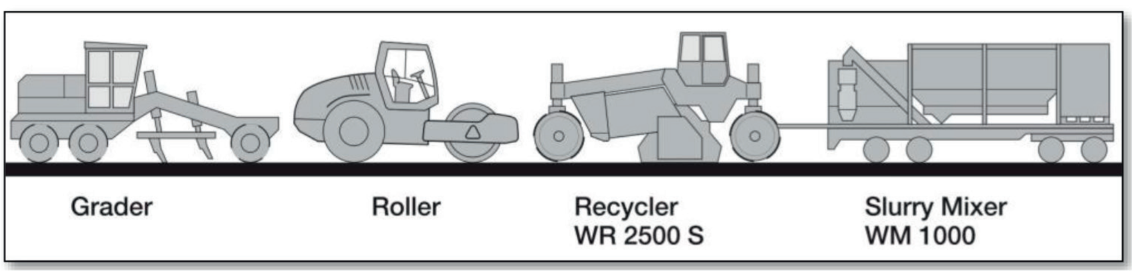

Figure 2.
Recycling train applying cement slurry [42].

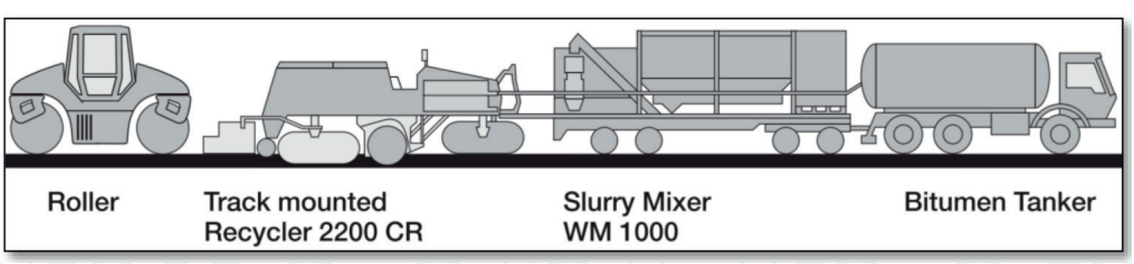

Figure 3.
A schematic of a recycling train using emulsion slurry [42].

pavement. The process continues with transporting the RAP to the asphalt plant and stockpiling the RAP. RAP in stockpile will be incorporated back into new HMA. In-place recycling offers a more cost-efficient method. In-place method eliminates the trucking and handling of the recycled asphalt by performing the complete process in one pass. In place method consist of hot in-place and cold in-place recycling.

Cold in-place recycling mainly occurs inside the milling chamber. Milling and mixing the recycled material with stabilizing agents like cement, bitumen emulsion, and slurry water combined in one single operation as shown in **Figure 1**. Meanwhile, the recycling train will have a different configuration that depends on the types of recycling application and stabilizing agent. Included in the train, there will be recycling machine as the locomotive that pushes or pull the embedded equipment.

Figure 2 shows a typical train for recycling with cement slurry stabilizing agent. The slurry will be pumped to the recycler with application rate metered before mixing (**Figure 3**).

2.2.1 Hot in place recycling

The rehabilitation process of old HMA pavement onsite, conducted in one operation, is called hot in-place recycling. The hot in-place recycling process starts with heating the asphalt pavement to a temperature that eases the process of milling. The process continues with RAP improvement by including virgin aggregate, and rejuvenator to the hot millings. Furthermore, the paver machine spreads and compacts the RAP. The type of processes hot in-place recycling are surface recycling, remixing, and repaving [23].

Surface recycling is the simplest one and can only rehabilitate the uppermost layer of pavement. Surface recycling starts with heating, continued by milling and placing the RAP without further processing except for rejuvenating agent that may be needed. Surface recycling is typically continued by a bituminous surface treatment overlay. The remixing process, on the other hand, allows recycling depth of 2 inches or more due to multiple passes of heating and scarifying. The remixing process also involves virgin aggregate and binder addition to the hot millings. Repaving places new HMA layer overlay above the hot in-place recycled lift. Hot in-place recycling was found to have less initial project cost and reduced length of lane closure as compared with conventional hot mix asphalt. Several other benefits of hot in-place recycling are as follows [23]:

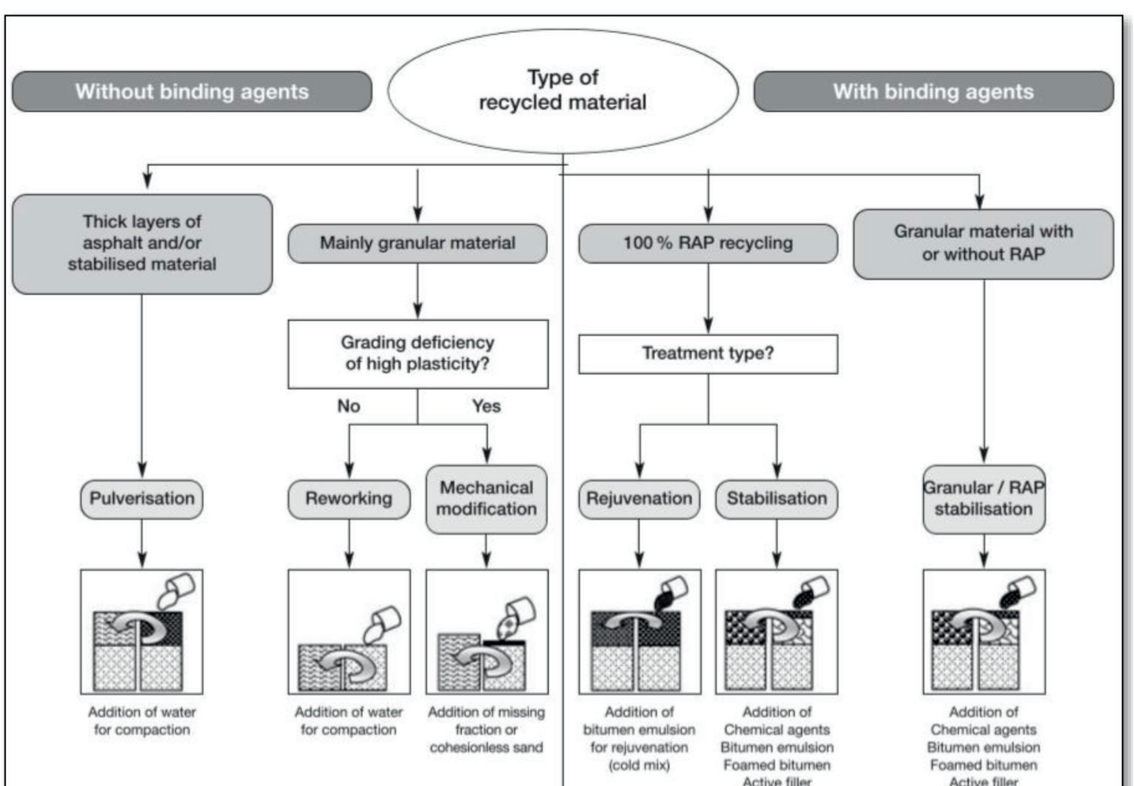

Figure 4.
Wirtgen's framework of cold pavement recycling [46].

- Recycling rate can achieve up to 100%.
- Less energy is used compared to the other rehabilitation methods.
- The amount of aggregate breakage is reduced due to heating and softening of the old asphalt pavement.
- Reduced transportation needed to move new material and stockpiling RAP.

2.2.2 Cold in place recycling

Cold in-place recycling is a method of aging pavement rehabilitation conducted at the project site. Therefore, Cold in place can reduce the need to loading and transporting material. The process includes milling and crushing the aging asphalt concrete, rejuvenating, and then laying and compacting the RAP. Asphalt pavements rehabilitated with cold in-place method were found to perform well [47]. Cold in-place is the recommended method for rehabilitating low-volume roads that have AADT of less than 2000, in Iowa, United States. Cold in-place roads have, on average, predicted service life from 15 to 26 years (**Figure 4**) [47].

3. Full depth reclamation: recycling and combining the asphalt Layer Base and subbase layers in-place

A portion or full pavement layer material from asphalt to subgrade is recycled through grinding and blending process to produce homogenous material. Typically, the blending product sufficiently performs as base material for new asphalt concrete layer even without stabilizing agents. However, project evaluation is required to assess the necessity of involving stabilization. Common methods of stabilization are mechanical, chemical, and bituminous. Mechanical stabilization uses granular materials such as virgin aggregate or RAP or crushed Portland cement concrete. Chemical stabilization uses lime, Portland cement, fly ash, cement kiln dust, or different proprietary chemical product. Bituminous stabilization is achieved by using asphalt binder, asphalt emulsion, and foam asphalt. A combination of these methods is also used for better stabilization.

3.1 Combining all layers—Full depth reclamation

3.1.1 Using cement

The widely used chemical type stabilization is cementitious agents such as lime, Portland cement, lime, type C fly ash, and blends materials. Stabilizing agents increase the particles' bonding and reduces the materials' plasticity. Lime stabilizing agent is typically used when the Plasticity Index of RAP is more than 10. Meanwhile, Portland cement is more often used if the Plasticity Index is less than 10.

The more stabilizing agent will increase the strength gain by the reclaimed material, but it is not necessarily better because increased amount of stabilizing agent may lead to a more rigid material. The increase in rigidity means that the reclaimed material is less prone to fatigue failure but has less performance against shrinkage cracking. However, shrinkage cracking related to cementitious materials can be alleviated by several methods such as lowering the application content but aligning with the mix design, maintaining compaction of the reclaimed mix to be below 75% saturation or below the optimum moisture content and control the rate of drying of the reclaimed mix. To better evaluate the amount of stabilizing agent, the physical properties of reclaimed mix with chemical stabilizing agent are related to the overall pavement design.

3.1.2 Using emulsion

Recent advances in chemical technology bring bituminous stabilizing agents to gain more popularity. Bituminous stabilizing agents are used in the form of asphalt emulsion. Asphalt emulsion as a stabilizing agent enables a mix between asphalt bitumen and cold reclaimed material. The compatibility in the chemistry aspect of asphalt emulsion and reclaimed asphalt material is important to form a stable bitumen-bounded reclaimed mix.

Better fatigue properties, less shrinkage cracking, and faster traffic opening were found in reclaimed mix with bitumen stabilizing agents compared with the reclaimed mix treated with cementitious stabilizing agents. The bituminous stabilized material behaves as a granular material with interparticle friction and as a viscoelastic material capable of withstanding repeated tensile stress. Bituminous stabilized mixes are susceptible to moisture effect due to high void ratio. The addition of Portland cement, lime, and fly ash combined with bituminous stabilizing agents can reduce moisture sensitivity. To significantly increase the strength or resistance to moisture, 1–3 percent addition by weight of reclaimed material is used. This amount of addition was found to not affect the fatigue properties and can be a catalyst to increase the gained strength of the reclaimed materials. If marginal quality is found in the reclaimed materials, it is common practice to use stabilizing agents consisting of bituminous and Portland cement or lime.

Figure 5.
Pill. Core from foamed bitumen stabilized asphalt layer [44].

3.1.3 Using foamed asphalt

Foamed asphalt is a cost-effective technique for stabilizing earth material, granular material, and bituminous material. The process mixes asphalt binder and water together to create a foamed asphalt which expands the size of asphalt approximately 17 times and allows it to coat soils and aggregate. The foaming process can be applied in place or in a central plant. Schwartz et al. [48] provided a recommended default design values for resilient modulus and structural layer coefficient are 300 ksi to 400 ksi and 0.30–0.35, respectively. Maryland State Highway Agency developed and adopted a standard specification Section 513—FOAMED ASPHALT STABILIZED BASE COURSE to provide best practice of quality control, equipment, acceptance for placing foamed Asphalt Stabilized Base Course. Typically, foamed asphalt will generate slight darkening of the new mixture as shown in **Figure 5**. This is due to uncoated aggregate and less bitumen found in foamed asphalt stabilized mixture. Foamed asphalt adheres to the fine particles and acts as a mortar that binding the particles. The advantages of foamed asphalt are the mix can work in various weather conditions and the asphalt can immediately be available for traffic after compaction.

3.2 Removing and treating individual layers

Instead of combining bituminous and non-bituminous layers, another approach treats and replaces individual layers. An example to that is the removal/milling of asphalt layers, piling the milled asphalt nearby and using a mobile central plant (such as Wirtgen's KMA 220) to process the material in the project vicinity. The material is then treated (with foam, cement, or emulsion as described in Section 3.1 then transported and placed. The advantage of this process is to allow a more precise control of pavement layers and utilizing the conventional layering system. **Figure 6** shows an example of a multi-step process where the top layer is milled out and processed using a central plant, the base is in place recycled then the plant processed asphalt layer is placed on top of the recycled base.

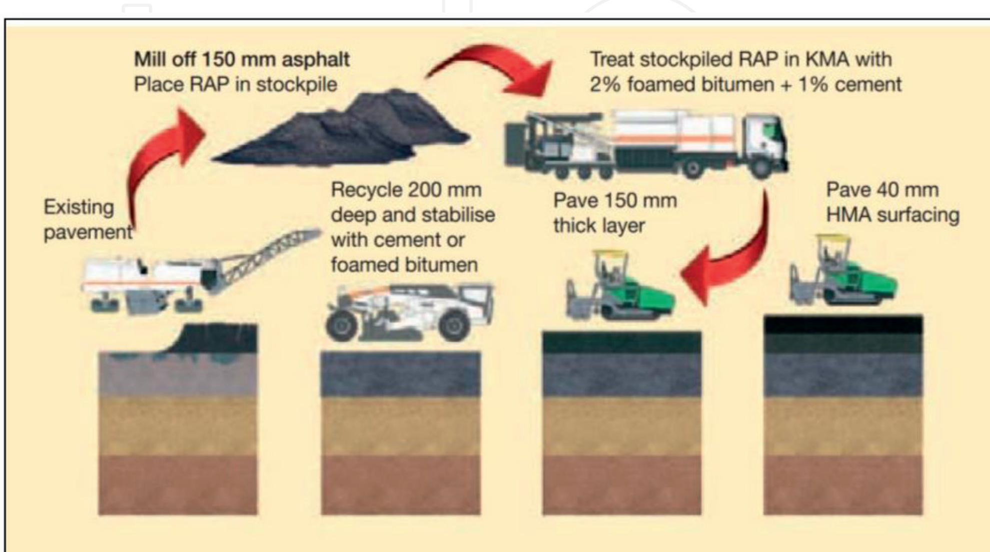

Figure 6.
Example of a 2-step process to peel and recycle individual layers [46].

Virginia Department of Transportation pioneered the use of pavement recycling techniques referenced above in high class roads, Interstate I-81, and used three different techniques: full-depth reclamation, cold centralplant recycling, and cold in-place recycling in the project. In order to accomplish the work, VDOT used a unique lane-closure schedule. An approximately eight months construction contract with valuation of $7.64 million was awarded in December 2010. VDOT published several reports and papers and provided several subsequent case studies for the nation on the use of best recycling techniques.

4. Conclusions

Pavement recycling is a clear way to achieve sustainability. This chapter provides a brief introduction and outlines the state of practice with respect to asphalt pavement recycling. The reuse of various pavement layers (asphalt, asphaltic base, granular base, and subbase) is discussed. The ways of utilizing the material, from the highest to the lowest economical use, are presented. The methods of recycling individual layers or combining multiple layers are discussed.

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Conflict of interest

The authors declare no conflict of interest.

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