# Using reclaimed asphalt pavement for sustainable development of highway construction: Article review

*Mahmoud Enieb, Ph.D.*
*Professor, Department of Civil Engineering, Faculty of Engineering, Assiut University, 71516, Egypt, Email: m.enie@aun.edu.eg*

**Abstract**: The use of reclaimed asphalt pavement (RAP) represents a recycling method with environmental benefits along with cost savings. RAP in new combinations of asphalt mixtures has benefits such as lowering the amount of virgin material, reducing cost and natural resources, and causing less environmental harm. In order to improve the physical and rheological characteristics of aged asphalt binders found in RAP, rejuvenators have been used. There are many types of rejuvenators for RAP binders, such as bio-oil, waste engine oil, and waste cooking oil. Foamed and emulsified asphalt have been widely used for their energy-saving and emission-reducing properties for cold mix-in-place (CIR) production. Hot in-place (HIR) recycling does not necessitate the transportation of significant amounts of new materials to the working site, there are fewer traffic noise and delays caused by cars coming and going from the work area. Finally utilizing cement to recycle the surface, base, and subgrade (full-depth reclamation (FDR)) to enhance the structural strength and durability of pavements.

**Keywords**: Reclaimed asphalt pavement (RAP), rejuvenators, hot mix in place (HIR), cold mix in place (CIR), full-depth reclamation (FDR).

## Introduction

Reclaimed asphalt pavement (RAP) is built from old asphalt pavement that has been milled or scraped off, and it is frequently used in new asphalt mixtures. A sustainable approach to asphalt pavement engineering should focus on materials, design methods, and technologies that can contribute to reducing environmental impacts by reducing energy consumption and natural resources, while ensuring that all performance standards and requirements are met [1]. During resurfacing, rehabilitation, or reconstruction projects, existing asphalt pavement components are frequently removed. The pavement material is removed and transformed into RAP, which contains the main aggregate and asphalt binder as shown in Figure 1. Sustainable pavement materials include economy, environmental, and engineering as shown in Figure 2 [2].

RAP is most frequently utilized in asphalt pavement as an alternative to virgin asphalt binder and aggregate, but it can also be used as an embankment or fill material, granular base, or subbase. RAP is a useful, high-quality material that can take the place of more expensive virgin binders and aggregates [3]. In an asphalt mixture, the asphalt binder is the most expensive and economically variable component. Materials are the most expensive component of production costs, making up 70% of the production cost as shown in Figure 3.

In particular, some of the required mix design parameters (such as voids in a total mixture (VTM), voids in the mineral aggregate (VMA), dust to effective binder ratio, etc.) limit the use of RAP due to the high fines content typically found in many RAP stockpiles.

**Fig. 1:** RAP milled [4].

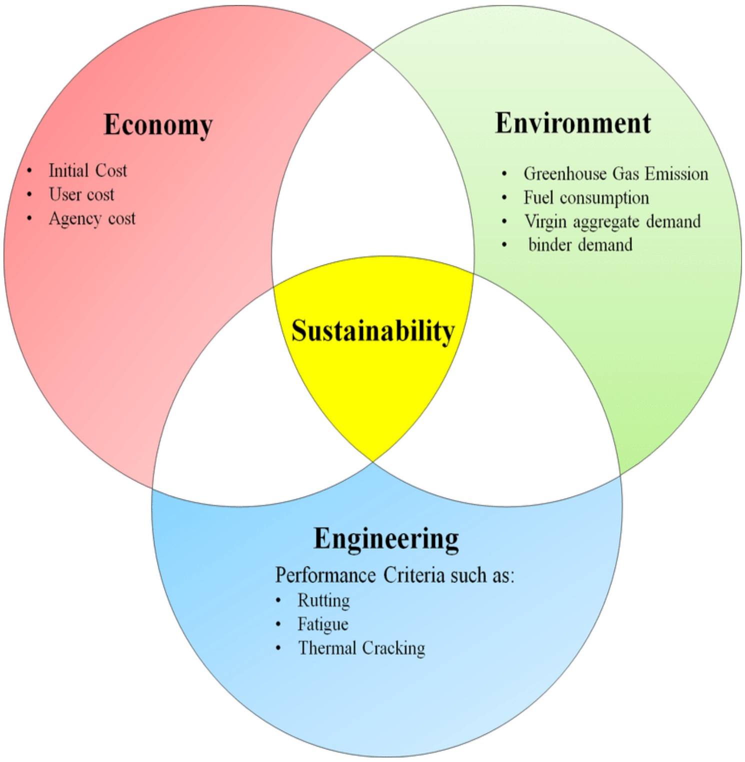



**Fig. 2**: Sustainability of pavement materials [2,5].

A lot of research has been conducted to investigate the effect of RAP inclusion in hot mix asphalt (HMA) on the mechanical and volumetric properties of such mixtures [6–10]. Because there was no need for further testing or adjustments to binder grades for these lower percentages, even while many HMA producers continued to employ RAP, the amount was often less than 15%.

The mechanical performance of the asphalt mixture is slightly affected when RAP is added at a lower rate, i.e., less than 20% [11]. The volumetric properties (VMA and voids filled with asphalt (VFA))) of the RAP asphalt mixtures were increased, according to Daniel and Lachance [6]. Marshall's stability and flow of the recycled hot mix asphalt were not considerably impacted by the addition of RAP materials to asphalt mixtures, according to Izaksa et al. [12]. According to Mogawer et al., Valdés et al., and Enieb et al. [4,5,13,14], the performance of asphalt mixtures with low RAP contents (less than 30%) were comparable to that of asphalt mixtures made from virgin materials.

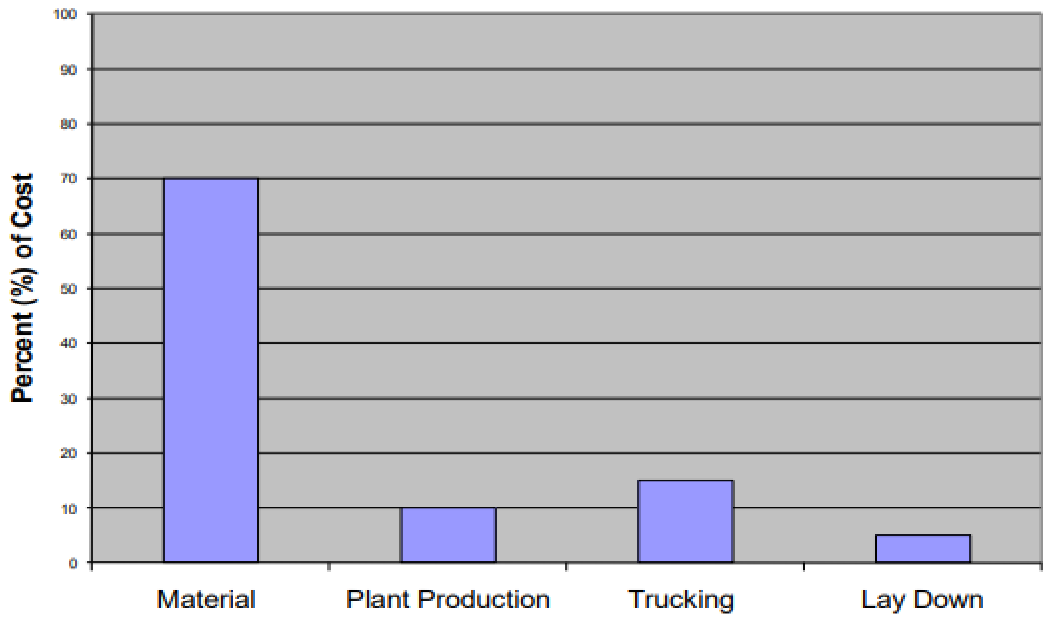



Fig. 3: Types of projected costs for asphalt construction [4].

However, when higher amounts of RAP are utilized (i.e., more than 30%), the asphalt mixture may be more sensitive to moisture damage and cracking [15]. Colbert and You [16] investigated the effect of RAP fractionated materials on the behavior of asphalt mixtures with different RAP content levels (50%, 70%, and 100% RAP). The reviews showed that increasing the concentration of RAP increases the viscosity of the RAP asphalt binders, which makes the mixture stiffer.

Utilizing a rejuvenator becomes important when using a higher RAP percentage. The pavement, on the other hand, becomes susceptible to rutting as a result of the unfavorable softening influence of the rejuvenator [10]. Researchers have studied the possibility of using rejuvenators in the past to make RAP binders less stiff [17,18]. Due to its similar physicochemical properties and molecular structure to the petroleum asphalt binder, light hydrocarbon oil such as waste engine oil (WEO) has been used to improve the properties of old asphalt [19]. WEO-rejuvenated binder has been found to enhance fatigue resistance and low-temperature healing performance. When compared to the control mixture, it was discovered that the WEO- crumb rubber rejuvenator enhanced the mechanical performance of HMA and enhanced the physical and chemical properties of the RAP-asphalt binder [9].

Waste cooking oil (WCO) is a viable waste material for the rejuvenation of asphalt binders, and many studies on its reuse have been conducted all over the world [20–22]. According to Zargar [23], adding 3-4% WCO to the binder's weight can enhance the penetration value, making the material more resemblant to virgin asphalt. Likewise, Asli [24] investigated the physical characteristics of WCO as a rejuvenator with RAP materials and recommends using up to 5% WCO without harming the performance of pavement mixtures while utilizing a rejuvenating agent in the mixture. In contrast, Ji [25] increased the WCO proportion to 8% to restore the aged binder's high-temperature resistance to rutting. Wen [26] did another trial in the USA and discovered that the use of a WCO-based binder increased moisture susceptibility and low-temperature resistance. However, the study found that as WCO-based binder was added to the mixture, the mixture's resistance to fatigue cracking, rutting, and stiffness was reduced. The majority of previous study on this subject only included physical and rheological tests, such as penetration [27], softening point [28], dynamic shear rheometer [29], and bending beam rheometer (BBR) [30] and they suggested that WCO may be used in the construction of asphalt pavement [22–24,26]. Numerous types of research have shown that various materials, including vegetable oils, waste-engine oils, and refining oils, can be used for rejuvenation [31].

The physical, rheological [32][29], and chemical characteristics of the RAP-containing binder were improved by the addition of a hybrid rejuvenator (HR) [33]. Styrene butadiene styrene (SBS) copolymer and aromatic oil (AO) were investigated as a rejuvenator. 25% SBS and 75% AO are combined to make up HR.

Effect of a mixture of 30% SBS copolymer and 70% wasted engine oil (WEO) as a composite rejuvenator (WS-rejuvenator) on the performance of mixtures comprising 30% and 50% RAP binders [10]. The results showed that at 5% and 10%, respectively, WS-rejuvenator regained the physical properties of asphalt binders containing 30% and 50% RAP.

Hashim et al. [34] used in their research noncommercial (WEO, WCO, date seed oil (DSO) ) and commercial (SonneWarmix RT) rejuvenators in asphalt mixtures incorporating RAP at three levels (20%, 40%, and 60%). According to the rutting performances, the best percentages for each type of additive utilized are found to be 10%, 12.5%, and 17.5% of WCO, 10%, 12.5-17.5%, and 17.5% of WEO, 10%, 12.5%, and 17.5% of DSO, as well as 0.5-0.9%, 1.0%, and 1.5-2.0% of the commercial rejuvenator, which correspond to the three selected RAP percentages.

Recycling road construction materials for reuse on new pavements is an important component of achieving the goal of “sustainable pavements” [35,36]. Reusing recycled asphalt pavement (RAP) has become a standard practice, especially when re-paving and re-establishing pavements [37].

As an introduction to the extensive use of nanomaterials in the pavement, we examine the possibility of using nano-silica fumes as an economical and practical alternative to expensive nanomaterials. A 6% Nano silica (NS)-modified binder is compared to employing high Nano silica fume (NSF) levels to improve the characteristics of basic asphalt from an economic viewpoint. It is possible to compute the pricing ratio (PR) and performance improvement ratio (PIR) as shown in Table 1.

Table 1: Fume nano silica-modified binders' economic advantages study [38].

| Binder type | Base asphalt | 6%NS-modified asphalt | NSF-modified asphalt | | | |
|---|---|---|---|---|---|---|
| | | | 20% | 30% | 40% | 50% |
| Price/kg (US $) | 0.35 | 134.5 | 0.367 | 0.373 | 0.378 | 0.383 |
| Price ratio (PR) | – | 384 | 1.05 | 1.06 | 1.08 | 1.09 |
| *PIR* | | | | | | |
| Penetration[a] | – | 2.14 | 1.63 | 1.97 | 2.14 | 3 |
| Softening point | – | 1.22 | 1.12 | 1.15 | 1.21 | 1.27 |
| Rotational viscosity | – | 4.98 | 2.35 | 3.29 | 4.58 | 6.69 |
| Critical temperature | – | 1.34 | 1.11 | 1.23 | 1.34 | 1.46 |
| (VTS)[a] | – | 1.24 | 1.18 | 1.22 | 1.21 | 1.22 |

[a]$PIR = PI_b/PI_m$, where the decrease in these measurements reveals an improvement in the asphalt properties

There are different types of RAP such as cold in-place reclamation (CIR), hot in-place reclamation (HIR), and full-depth reclamation (FDR). Short details about each of them are below.

**Cold in place of reclaimed pavement (CIR)**

As the most used material in the pavement industry, the asphalt mixture of various distress, such as rutting and cracking, suffers throughout the service period. Removal of old asphalt pavement results in a large amount of RAP materials. The use of RAP in new asphalt mixtures has become a mainstream practice with many advantages, including reduced energy and emissions, saving on non-renewable materials, conserving landfill space, and lowering production costs [39]. In CIR foam asphalt and emulsion-based mixtures have been widely used for their energy-saving and emissions-reducing features.

In the CIR method, specialized equipment or processing trains are used to mill the existing pavement surface to a depth of up to 150 mm (6.0 inch), process it, combine it with asphalt emulsion or foamed asphalt, and then lay it down and compact it all in one motion. Before the recycling process, no processing is necessary [40]. There are different estimates of optimum asphalt content, optimum water content, and processing conditions because different countries have not formulated clear requirements for CIR design [41,42].

The Marshall approach [43], and the Superpave method [44], are some of the most widely used design methodologies for CIR in the US. The Marshall approach and Superpave method [45] do not balance volume properties and performance properties, and they are not completely dependent on pavement performance. The unavailability of recognized standards is the lack of a mixture design approach that balances the properties of size and performance characteristics the most important challenges in the progress of CIR technology. By reviewing and discussing raw materials related to and mixing the mixture, this review hopes to help continue the progress and popularization of CIR technology.

The properties of each component of the final cold place asphalt mixture, including RAP, asphalt, aggregate, regenerator, and stabilizer, affect how well your pavement performs overall. Therefore, it is necessary to evaluate the materials composing a CIR mixture separately during construction [46]. Since the RAP aggregate is considered black rock, the aged asphalt it contains was not considered when designing the CIR process. The overall performance of the recycled pavement will be impacted by the presence of old asphalt on its surface. Usually, the total binder consists of virgin asphalt in mixtures and aged asphalt in RAP. To reduce the viscosity [47] of all types of asphalt, an emulsifier or foaming agent is required. According to AASHTO specifications, there are two main techniques for determining the amount of asphalt in RAP: solvent extraction [48] and ignition [49]. Rheological properties such as penetration value [27], a viscosity [47], etc. can be used to evaluate the performance of aged asphalt. In terms of thermal cracking performance, combinations with a 40% RAP component outperform pure RAP [50].

RAP particle agglomeration is one of the most important factors affecting CIR performance. When the RAP particles agglomerate together, the moisture stability of the cold recycled asphalt mixture and the fatigue resistance will become poor [51]. The bond between the RAP and the binder was enhanced by properly crushing the RAP, adding virgin aggregates, and using a fine-grading design. This led to a decrease in the agglomeration of the RAP [52]. In order to increase the coarseness of the gradation, the recycled materials should be supplemented by fresh aggregates at an appropriate point of the process [53].

The Marshall design method [43] is now the most comprehensive and popular method for asphalt technology. This technique, which essentially uses volume, places restrictions on the mixture density [54], total void ratio, and mineral void ratio. Water content is a key component of an improved Marshall process. The approach requires that the proposed aggregate has 3% of its total weight in water (water as an emulsion and water in RAP plus additional mixing water) [55]. Pi et al. (2017) created cold-recycled asphalt mixtures using the improved Marshall method and evaluated the technical performance values of the mixtures, such as elevated temperature stability, moisture sensitivity, and fatigue performance [56]. Cold recycled emulsified asphalt mixes meet the needs of the lower layer and the road base layer and have good high-temperature stability and moisture sensitivity. The distribution of design methods is shown in Figure 4 from the studies of the many reviews.

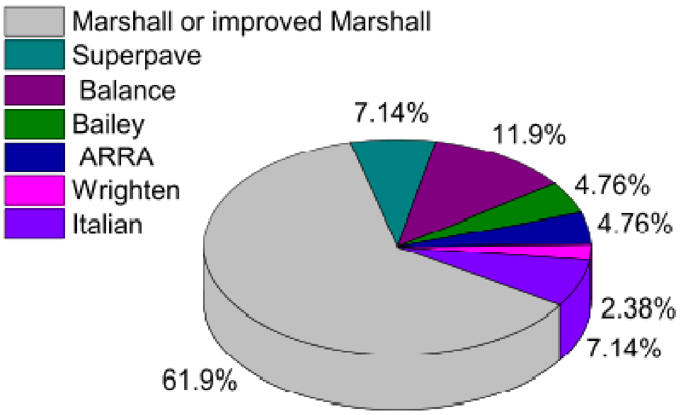



Fig. 4: The percentage of design methods in the study under consideration [39].

Asphalt stabilizers come in two main types: foam asphalt and emulsified Asphalt. A variety of flooring materials can be supported by any of these stabilizers [57,58]. Figure 5 displays the corresponding ratios of the various stabilizing agents.

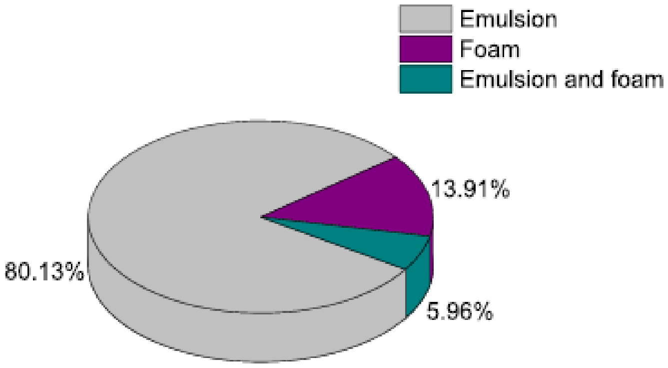



Fig. 5: Percentage of different types of stabilizers used in several related articles [39].

**CIR-foam mixes**

Recent developments have focused attention on the use of foam asphalt in CIR projects due to the advantages of high strength, adaptability to stable bitumen material, faster construction, less maintenance, and quick resumption of regular traffic flow [59].

The most common chemicals used as stabilizer agents are cement and lime because of their inexpensive cost and wide availability [60]. Based on the information obtained limestone is highly recommended as an active filler [61].

The mix design was carried out with RAP materials in addition to assessing the consistency of a new CIR-foam mix design process. Instead of utilizing a Marshall hammer to create the test specimens, a gyratory compactor [62] was used because it created more uniform mixtures for a range of foamed asphalt contents and curing circumstances. The vacuum-saturated specimens made from each of the seven RAP material sources were tested for their indirect tensile strength at five different foamed asphalt contents (1.0, 1.5, 2.0, 2.5, and 3.0%), with a fixed moisture level of 4.0%. Air voids in the CIR-foam mixes gradually reduced as the foamed asphalt concentration increased from 1.0 to 3.0% at 0.5% intervals. CIR-foam specimens that were treated for two days at 60°C had an indirect tensile strength that was considerably higher than specimens that were treated for three days at 40°C. Based on the new mix design process, the ideal foamed asphalt contents for each of the seven RAP materials were consistently found to be between 1.5 and 2.5% [63]. The design procedure of CIR is shown in Figure 6.
It is advised that the foamed asphalt content be adjusted using RAP materials that have been conditioned at the field temperature following the laboratory mix design. The paver operator should keep an eye on the CIR-foam mixtures in the field as the temperature changes from a cool morning to a hot afternoon, especially in the early spring and late fall. It is recommended that RAP materials heated to a temperature that will approximate the temperature of the field's existing asphalt pavement be used to produce the CIR-foam mix design [64]. The following graphic shows the production of the CIR-foam mix.

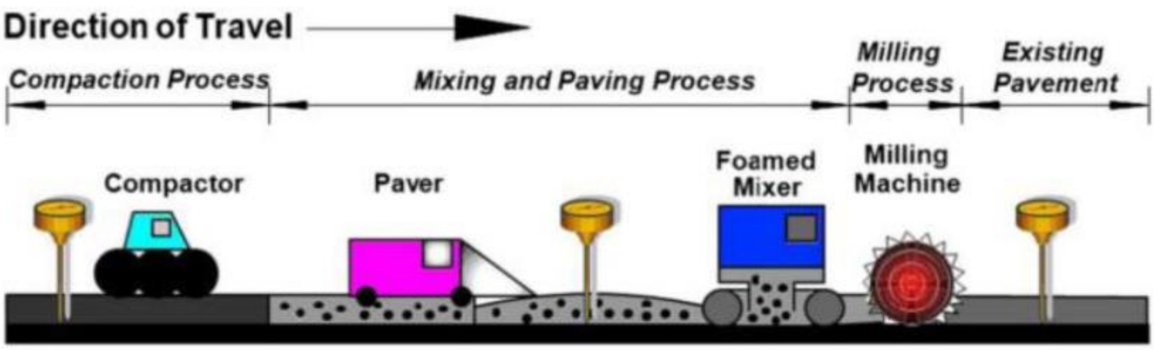
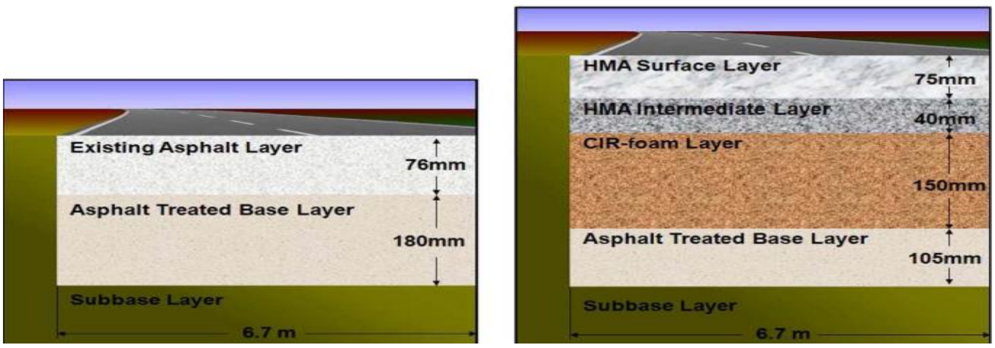



Fig. 6: The CIR's common procedures [64]

As shown in Figure 7(a), a 6.7m-wide asphalt pavement with a 76mm-thick HMA layer and a 74mm-thick asphalt-treated base layer was milled and mixed with foamed asphalt to produce a 150mm-thick CIR foam layer (Figure 7(b). A 40 mm thick HMA intermediate layer and a 75 mm thick HMA surface layer were then overlaid on top of the CIR foam layer.




(a) Existing pavement (b) Cross section after CIR-foam layer.

Figure 7: Existing and repaired pavement cross sections [64].

The foamed asphalt can be manufactured at the site or in a central factory and Lab as shown in Figure 8. The contents of the binder depend on the mixture design and are determined as a percentage (weight) required for the mixture to have perfect properties [65]. Bitumen and water are combined to produce foamed bitumen. It is produced by injecting water into air-supported, heated bitumen (160–180°C). Water volumes between 2 and 5 percent of the volume of bitumen.

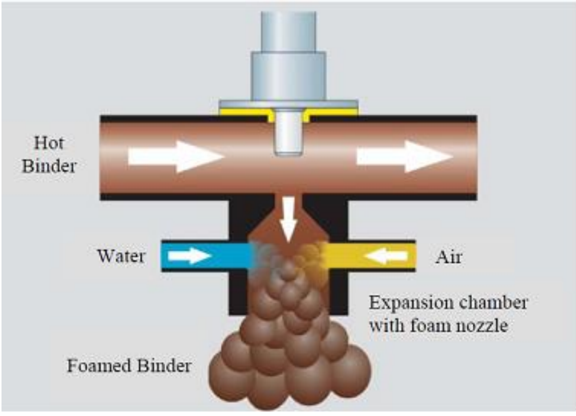




Fig. 8: Laboratory-Scale Foaming Device (WLB 10 S): Foaming Nozzle and Foaming Device [66], [67].

**CIR- emulsion mixes**

HFMS-2 (High-Flow Medium-Setting with a Solvent), HFMS-2p (High-Float Medium-Setting modified with a Polymer), CSS-1 (Cationic Slow Setting), and other emulsions are frequently used as recycling agents. Table 1 displays the properties of the three types of emulsified asphalt described.

Table 1: Types of emulsions that are used in CIR [39].

| Emulsion | Definition | Properties | References |
|---|---|---|---|
| HFMS-2s | High-flow medium-setting with solvent | Stability, faster setting, and better workability in summer; High float; Require additional solvents in process. | [68] |
| HFMS-2p | High flow medium setting emulsion modified with a polymer | Like HFMS-2S; Modified with a polymer; Recycled mixes have better stability and are more stable. | [69,70] |
| CSS-1 | Cationic slow setting | Do not require the solvent in process, Sufficient workable duration, Sufficient workable duration, Be sensitivity to rain | [71–74] |
| CMS | Cationic medium setting | Faster set emulsion. | [75] |

Recycled asphalt pavement (RAP) was still 4:1 in weight to virgin aggregate and mineral powder. Aggregate gradation [76,77] for CIR design specifications, such as ASTM C136, 117 [76,77]. The criteria for emulsions were based on the results of the coating test [78]. The amount of asphalt emulsion is kept at 4.0% by weight of cement, aggregates, and mineral powder, and the tested water contents are 3.0%, 4.0%, 5.0%, 6.0%, and 7.0% by weight of cement, aggregates, and mineral powder [79]. The optimum water content is the amount of water that is present when the bulk density reaches its highest value.

The indirect tensile strength (ITS) test was carried out after molding the Marshall sample and sensitivity testing to moisture according to ASTM D1075 [80]. ITS was obtained following ASTM D6931 [81]. The wheel tracking test was performed to evaluate the stability at high temperatures [82].

To examine the reclaimed asphalt's complex modulus, a dynamic shear rheological test was conducted [29]. The temperature range was between 10 and 25 $^{o}$C, and the temperature sweep mode was used. Separately, the control frequency and strain were set at 1% and 10 rad/s [79].

Niazi and Jalili demonstrated that Portland cement and lime can both enhance the Marshall stability [83], resilient modulus [84], tensile strength, resilience to moisture damage, and resistance to permanent deformation of CIR mixtures. Portland cement and lime slurry produced greater results than hydrated lime, although it is advised to use Portland cement instead because it is simpler to manufacture [85].

Since previous research [86] has shown that Portland cement and lime can shorten the time it takes for bituminous emulsions to crack, the decrease in curing time may be the cause of the mixtures' increased stability. The maximum resilient modulus value was obtained by using 2% Portland cement because Portland cement stiffens the binder [85].

Dong et al. demonstrated how adding a rejuvenation agent, and styrene–butadiene rubber latex can enhance the overall performance of the modified CIR-emulsion mix. These results support the choice of modifiers to raise the reliability and performance of CIR-emulsion asphalt in practical engineering applications [87]. In comparison to conventional materials, the modified materials showed a higher overall performance.

**Benefits of CIR:**

Environmental advantages: Due to the reduced need for material delivery, CIR diffusion reduces noise pollution from heavy vehicles [88]. In addition, a decrease in motor vehicle transportation leads to a reduction in greenhouse gas emissions. Furthermore, since CIR technology is based on the cold asphalt, the temperature of the mixing system is usually kept at ambient levels during the construction process. CIR also reduces fossil fuel use and associated greenhouse gas emissions by removing the additional fuel consumption needed for heating in HIR [89].

Operational advantages: road recycling uses framing, mixing, paving and compaction systems that improve comfort and safety for both construction and transportation [90].

Sustainable advantages: To produce new RAP aggregates, the recycled asphalt pavement can be recycled once again, eliminating the requirement to test recently obtained RAP before construction [89]. Equipment advantages: The technology employed in CIR is quite advanced [35].

**CIR limits:**

Adjustments must be made in line with the environmental conditions of the construction site due to the need for a curing period and covering layers. It is difficult to control pavement quality. There are no defined and widely recognized design approaches, and on-site environmental conditions differ from laboratory-based design scenarios. Only the bottom layer's high-grade or lower-grade pavement layers can be used with CIR in the conventional sense.

**Environmental and economic assessments**

Rehabilitation methods are created for a similar service life. As a result, an economic study compared initial expenses. The AASHTO Practical Guide Handbook of Cost Estimation of Road Engineering Projects was used for cost estimation [91]. Based on technical, environmental, and economic considerations, selected paving systems were determined after evaluating the initial expenditures. Energy and carbon dioxide emissions of the various materials and construction processes studied are shown in Tale 3 [92]. Accordingly, the amount of energy use and pollutants generated will be calculated for each type of construction.

Table 3: Carbon dioxide emissions and energy of various materials construction [93].

| Type of materials or methods of construction | $CO_2$ (kg/t) | Energy usage [Mega Joule (MJ/t)] |
|---|---|---|
| Processed aggregates for HMA | 10 | 40 |
| Production of cement | 980 | 5000 |
| Bitumen production | 285 | 4900 |
| Bitumen emulsion production | 221 | 3490 |
| Lime | 1500 | 5500 |
| Production of HMA | 22 | 275 |
| Surface milling of asphalt for CIR | 0.8 | 12 |
| Deteriorated asphalt removal | 0.4 | 8 |
| CIR and stabilization | 1.1 | 15 |
| Laying and compaction of HMA | 1.1 | 14 |
| Laying of cold mix | 0.4 | 6 |
| Coating with bitumen emulsion | 27 | 310 |
| Lorry transport (km/t) | 0.06 | 0.9 |

**Hot in-place (HIR) recycling**

Because of its sustainability and high construction standards, hot in-place recycling (HIR) is one of the alternative technologies that agencies can use to rehabilitate pavements. The method starts by heating the old HMA pavement to a temperature that enables scarifying or milling machinery to quickly remove the top layer of the existing HMA pavement from the road surface [94]. Some HIR processes add aggregate, asphalt, and rejuvenator to the hot millings after they have been removed from the road to enhance the qualities of HIR pavement. As part of the hot HIR process, a train of machinery heats asphalt to 121 $^{o}$C, grinds it, adds aggregate and rejuvenating oils, and then mix the asphalt. By comparing performance parameters such as binder grade, volumetrics properties, and performance tests to the qualities of the original Superpave combination and the mixture following hot in-place recycling [95]. The recovered material is then distributed and compacted using standard paving machinery. Three HIR procedures are identified by the Asphalt Recycling and Reclaiming Association (ARRA): surface recycling, remixing, and repaving. The researchers investigated how the incorporation of RAP materials affects some asphalt mixture properties such as resilient modulus, moisture resistance, permanent deformation, and fatigue. The resilient modulus has improved in up to 30% of the RAP and is less affected by moisture damage than the virgin mixture [14].

To the guidelines in the Basic Asphalt Recycling Guide [3] for HIR Pavements, laboratory tests were performed as follows [95]:

- Binder performance grade (PG).
- Penetration/ viscosity of the binder.
- Mixture gradient.
- Asphalt content (AC).
- The Superpave system's most crucial design element is a mixture of air voids.
- Hamburg test results for mixture rutting resistance.
- The Hamburg test and the Indirect Tension test are used to measure a mixture's resistance to cracking and moisture damage.

The following procedures are listed by the American Recovery and Reinvestment Act (ARRA) for the construction of HIR.

Analyzing the current HMA pavement.
Determining the needs for recycling agents.
Determining the necessary additives.
Making and evaluating sample mixtures.
Choosing the best mixture.

The gradation and binder characteristics of the existing HMA pavement must be known to create an HIR mix, just as it is necessary to know the qualities of the asphalt binder and the aggregate stockpiles in order to construct a conventional HMA mix. Testing of samples from the road is necessary to determine the gradation and binder properties of the current HMA pavement. The recycling component helps make the mixture more compressible so that sufficient compaction can occur at temperatures lower than those of standard HMA. HIR's compaction temperature range is 90 $^{o}$C to 115 $^{o}$C.

Hot-in-place recycling is reported to result in significant cost savings, with HIR costs expected to be 30% lower than those associated with the traditional method of milling and repaving [96]. With an in-place mixing procedure that uses less energy by heating only to 121 $^{o}$C, HIR can decrease the energy used at the asphalt plant to heat the aggregate and asphalt mix at 177 $^{o}$C. The fuel used to heat the asphalt in HIR is propane, a waste product of the processing of natural gas and the refining of crude oil. Propane produces less pollution than gasoline and diesel used to construct new pavements. The volumetric properties of the final mixture are tested after the base binder and Job Mix Formulae (JMF) are ready. Figure 9 shows the step-by-step method for forming mixtures.

Table 2 shows the effect of the RAP ratio on the binder performance grade (PG) used to obtain the base binder PG.

**Table 2:** Effect of RAP percent on binder grade [97]**.**

| RAP percentage | Binder grade used with HIR |
|---|---|
| 0 to 15% | No change in the base binder grade |
| 15 to 25% | Reduce one grade |
| >25% | Binder evaluation (recovery, blending, etc.) [98] |

From the point of view of economy, RAP components still have value, especially for asphalt binder, it can reduce the amount of new asphalt binder in mixture, 20% RAP with 5% asphalt content. 1% savings in new asphalt binder.

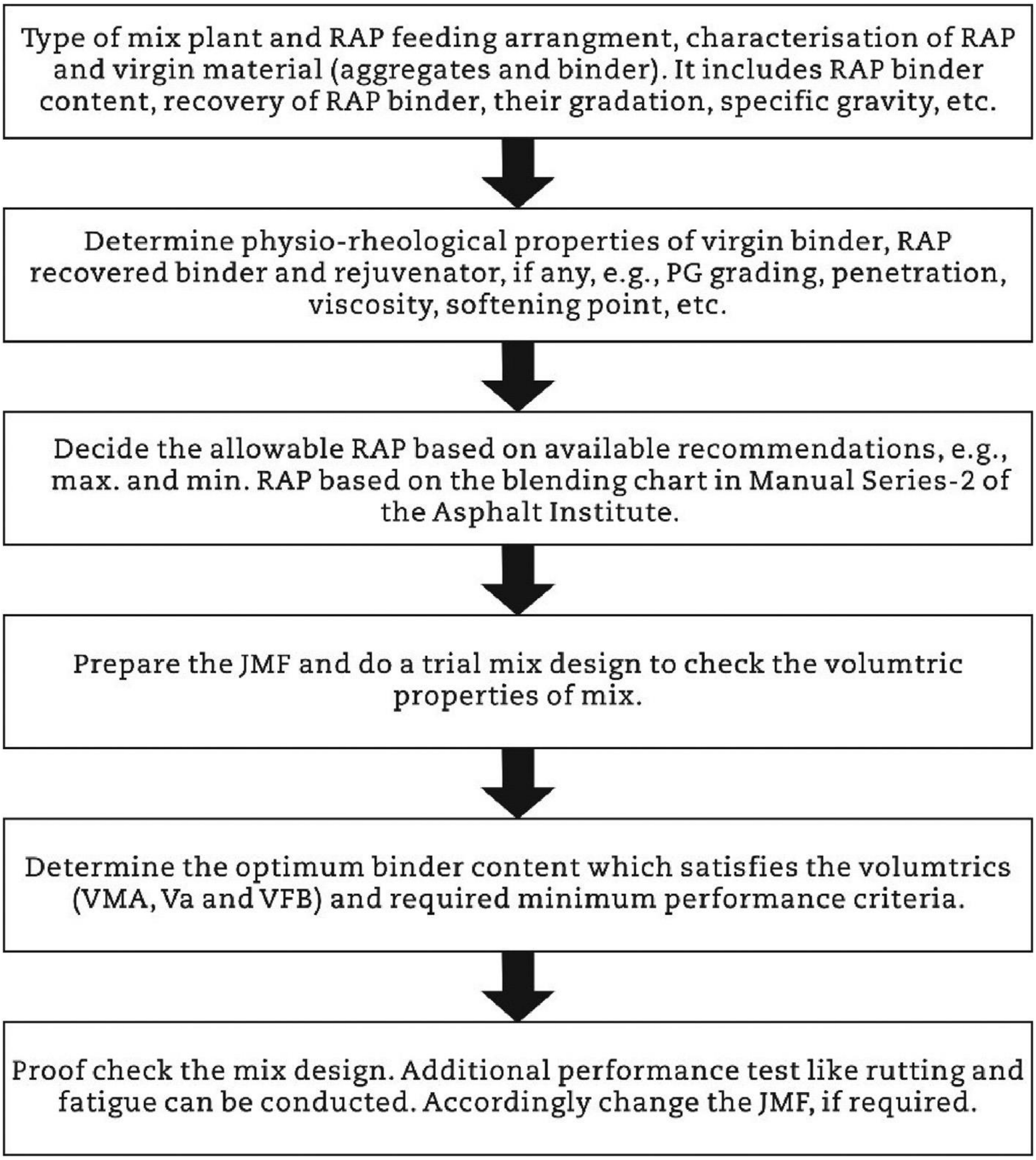



**Fig. 9**: RAP-HMA mixture design process [1,96].

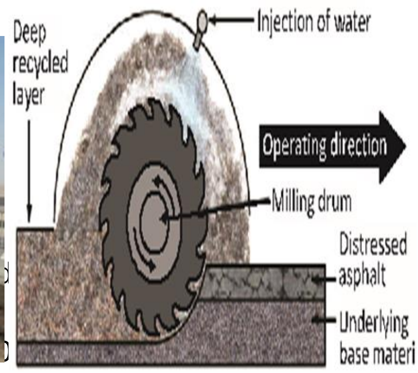
**The following are the advantages of HIR:**

- By recycling all the existing pavement, HIR eliminates the need for additional aggregate and asphalt [99].
- Energy efficiency compared to other rehabilitation techniques.
- Compared to the cold method, heating and softening the existing HMA pavement before planning minimizes the quantity of aggregate fracture.
- There are fewer traffic disruptions caused by vehicles entering and exiting the work area because HIR does not require transporting large quantities of new materials to the job site.

- Traffic can move through the work area more quickly because the shorter lanes are closed, which reduces delays.
- Compared to conventional HMA, HIR pavement is less expensive initially.

**Full-depth reclamation, FDR**

FDR, or full-depth reclamation of asphalt pavement, is a rehabilitation technique that involves recycling existing asphalt pavement and any underlying layers into a new base layer. Figure 10 shows how the first step in the FDR process is to use a road reclaimer to grind up some of the existing asphalt pavement and the base, subbase, and/or subgrade. The crushed material is usually uniformly mixed with an added stabilizer, such as Portland cement, to produce a more homogeneous composition. The stabilized material is then crushed into place by rollers. Since the base is now rigid and stable, a new rigid or flexible surface course can be applied. Table 3 presents the types of pavement treatment procedures.




| Method | Advantage | Disadvantage |
|---|---|---|
| Thick structural overlay | New pavement structure. Quick construction. Little traffic disruption | Importing a large amount of material is necessary; upgrading an old base or subgrade may still be necessary; and the more expensive alternative. An elevation change may cause issues with the curb, gutter, and overhead clearance that are already in place. |
| Removal and replacement | provides new pavement construction; removes failed base and subgrade; You can keep the current road's height and profile. | Long construction cycle requiring alternative routes and causing confusion to nearby residents and businesses, Increased traffic congestion due to diversions, construction traffic, Rain or snow can significantly delay completion, a large quantity of materials must be |

| | | |
|---|---|---|
| | | imported, Old materials must be safely removed of, Highest cost alternative, May require additional work to fix subgrade problems, and Large carbon footprint |
| Utilizing cement to recycle the surface, base, and subgrade (full-depth reclamation) | Newly constructed paving structure, Minimal elevation change, which eliminates curb and gutter and overhead clearance issues; Short construction cycle; Moderate traffic disturbance; Local traffic quickly resumes; rain has little impact on construction schedule; provides moisture- and frost-resistant base; is a least expensive alternative; requires thinner surface course than conventional construction methods; requires minimal material to be transported in or out; conserves resources by recycling existing materials. | Fixing issues with the subgrade might require further work.<br>A bituminous surface may reflect some shrinkage cracks. |

The new road's structural capacity is enhanced by full-depth cement reclamation because it creates a more solid and stable base. FDR is frequently used to repair old or structurally damaged flexible pavements as a result of base and subbase problems. Typically, FDR treatments are between 25.0 cm and 30.0 cm thick. Pavements with a thick layer of asphalt concrete (AC) should be milled to the necessary depth, then FDR should be applied. Four processes make up the FDR construction process: pulverizing the old pavement, stabilizing, shaping, and compacting [17]. The FDR mix design determines the amount of water and cement needed to achieve the required unconfined compressive strength (UCS) using typical field samples. As adequate moisture is one of the most vital factors in FDR building, the pulverized mix with cement is frequently compressed to slightly on the wet side of the optimal moisture content. A compaction test, gradation test, finished surface profile, thickness, and UCS on cores taken from the FDR base after a 7-day cure time are often used to evaluate the quality of FDR with cement. The recommended UCS is in the range of 1.4 MPa (200 psi) (Ohio for thin asphalt concrete pavement) and 3.8 MPa (550 psi) (California) [101,102]. The stiffness of the FDR base layer is increased by adding more Portland cement, however, too much cement can cause problems that are not connected to loads, like transverse shrinkage cracking. RAP content, RAP type, and base type were all factors that Guthrie et al. investigated about the mechanical qualities of cement-treated base materials in northern Utah [103]. The use of materials with a high RAP content also reduces their sensitivity to moisture. According to the researchers, adding 25% of RAP reduced strength by 29% compared to the neat base material, and strength decreased by 13% to 15% for every additional 25% of RAP [104].

The process of creating the mix should be systematic and scientific, balancing required and actual engineering features, buildability, durability, and economy. Figure 11 shows the general steps in selecting a mixing design for the FDR layer and the proportion of cement required to the volume of different types of soils presented in Table 4.

Table 4: Cement Requirements for AASHTO Soil Group

| AASHTO soil group | The usual range of cement requirements | | Estimated cement content and that used in moisture-density test, percent by weight | Cement content for wet dry and freeze-thaw tests, percent by weight |
|---|---|---|---|---|
| | The Percent by vol. | The Percent by wt. | | |
| A-1-a | 5-7 | 3-5 | 5 | 3-4-5-7 |
| A-1-b | 7-9 | 5-8 | 6 | 4-6-8 |
| A-2 | 7-10 | 5-9 | 7 | 5-7-9 |
| A-3 | 8-12 | 7-11 | 9 | 7-9-11 |

**FDR advantages:**

There are many advantages to full-depth reclamation, including those listed below:

- Cost-effectiveness.
- Enhanced structural strength and durability (compared to granular base materials).
- Possibility of enhancing road geometry.
- Expedited construction schedule and improved staging early start of traffic.
- Reduced effects of construction on the environment.
- Decrease in carbon footprint.

**Economic study for the case study:**

Below is a case study from Mina Road, Egypt according to the Roads and Bridge Works Consideration List for the 2022 edition.

| FDR | Normal maintenance (NM) | Unit | Item price (EGP) | |
|---|---|---|---|---|
| | | | FDR | NM |
| FDR 25 cm | -------- | $M^2$ | 55 | - |
| Cement | ------- | 25 kg/ $M^2$ | 25 | 75 |
| ------ | Base 25 cm | $M^2$ | | 75 |
| MCO | MCO | $M^2$ | 25 | 25 |
| --------- | Bonding layer | $M^2$ | | 145 |
| ------- | RC | $M^2$ | | 8.35 |
| Surface layer | Surface layer | $M^2$ | 125 | 125 |
| Total | | | 230 | 378.35 |

It is clear from the previous table that 39.1% is saved per square meter when using FDR technology in road maintenance works.

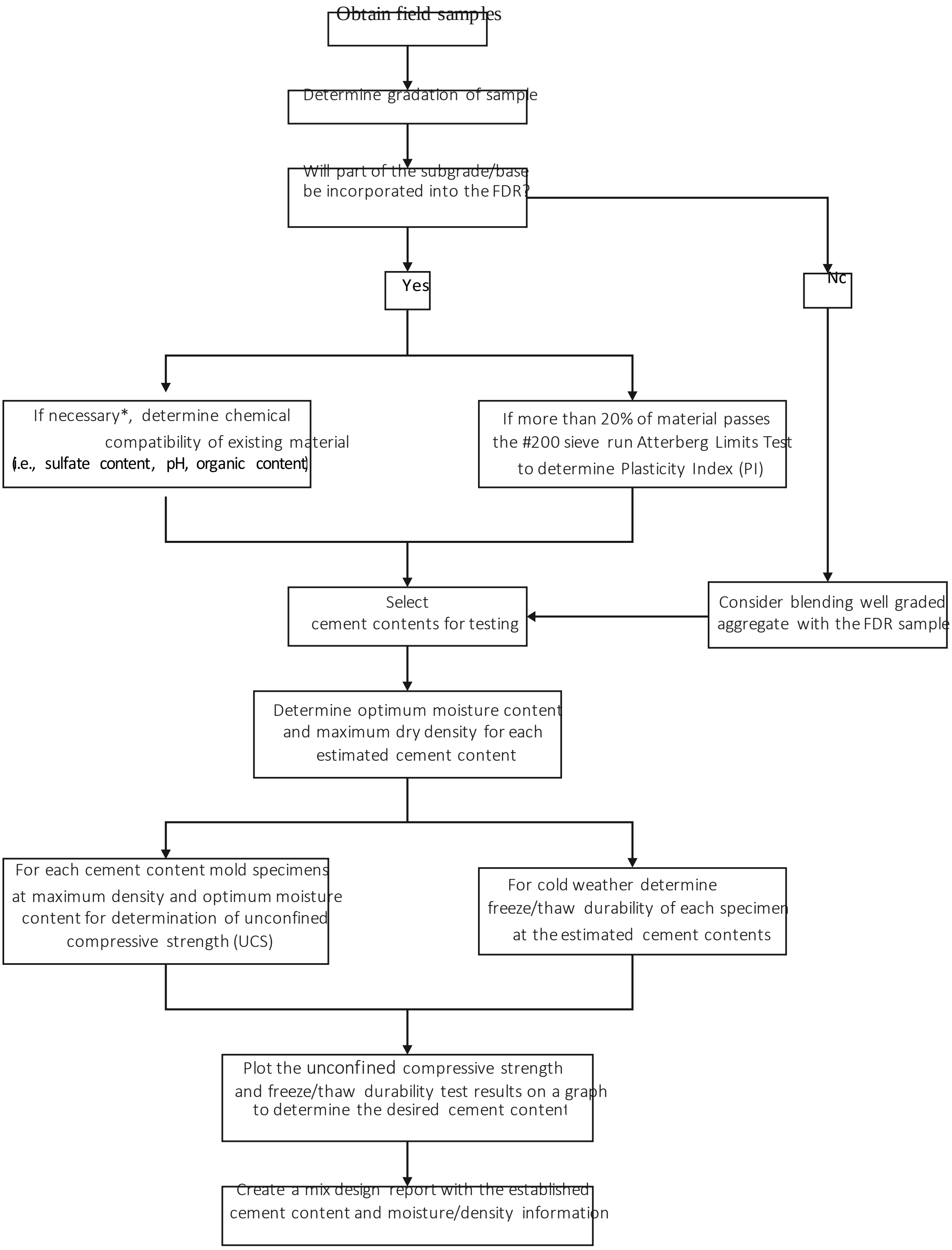



Fig. 11: General procedures for calculating mix design for FDR layer [105].

## Conclusion

The following is a summary of the most important conclusions from this review:

- RAP is a useful, high-quality material that can take the place of more costly virgin binders and aggregates.
- The same mix design requirements that apply to virgin mixtures must also be met by RAP mixtures. The Marshall and Superpave method are the most widely used design mixing method for RAP mixtures, including high RAP.

- The performance and durability of pavements containing up to 30% RAP are similar to that of virgin pavements free of RAP.
- Specification limitations, lack of processing, lack of availability of RAP, and previous experiences are some of the most common challenges to scaling up RAP implementation.
- The Superpave design approach should be given the primary priority in the design of CIR asphalt mixtures, according to our comparison of Marshall and Superpave methodologies from the corresponding points of view.
- Emulsified asphalt is likely to be used by researchers while designing cold-in-place reclaimed asphalt mixes.
- The stiffness and thickness of the FDR base layer have a significant influence on the predicted pavement performances.
- If the subgrade material under the FDR layer is soft and will not support the FDR layer enough, the repair must be found first

**Recommendations**

- The author believes that construction test sections of recycled and conventional mixes will confirm the adaptability of asphalt mixes incorporating RAP to loads and climatic conditions in Egypt.
- For mixture design purposes, the RAP material must be accurately classified. The RAP component should be used to create the laboratory mixture design.
- The planned asphalt mixture containing RAP, especially high RAP, should have its mixture performance evaluated. For assessing the performance of compacted asphalt mixtures in terms of potential permanent deformation, fatigue, and thermal cracking, several performance tests are available.
- A pavement management system should be taken into account with documentation of the use of the RAP which includes information on types, sources, and placement of the RAP.
- To study the impact of various RAP with various qualities on combinations with various rejuvenators, it is important to take into account more than one source of RAP.
- It is important to conduct more research on the short- and long-term aging behavior of RAP mixes containing various rejuvenator types.
- Investigating the impact of rejuvenator ratio, and RAP% on mixture parameters for long-term performance.
- Utilization of various grades of pentation (Pen), particularly high penetration with RAP combinations, to decrease brittle stiffness.
- Study the effect of bio-oil, waste vegetable oil, and anti-stripping agents on the performance characteristics of RAP mixtures modified with crumb rubber.
- The future design methodology will advance in the direction of CIR asphalt mixtures, which includes the performance index and volume index.
- In field operations, the paver operator should monitor the condition of CIR foam mixtures as the temperature changes from cool mornings to hot afternoons, especially in early spring and late fall.
- Study the effect of different types of cement on the properties of FDR.

- In order to undertake FDR pavement design using AASHTOWare Pavement ME Design (PMED) software, additional study is required to produce design input values, such as modulus of elasticity and modulus of rupture for the FDR foundation.
- Stricter control over the cement distribution rate and treatment depth will be required to minimize the strength variations. Additionally, a variance will be decreased by taking sufficient field sampling of the current pavement materials for mix design.
- Continue to evaluate the rutting performance of the trial sections in FDR and compare it to the usual rutting distress limits.

**References**


[1] Asphalt Pavement Association of Michigan. RAP-HMA mixture design process. Available at: Http://WwwApa-Mi Org/Docs/RAP2012LRWPdf (Accessed 14 April 2020) 2014:104.

[2] Thomas J. Van Dam, John T. Harvey, Stephen T. Muench KD, Smith, Mark B. Snyder, Imad L. Al-Qadi, Hasan Ozer JM, Prashant V. Ram, Jeffery R. Roesler and AK. Towards Sustainable Pavement Systems: A Reference Documen: Report No. FHWA-HIF-15-002. Federal Highway Administration May 2012 – January 2015 1200 New Jersey Avenue, SE Washington, DC 20590 2015.

[3] Asphalt Recycling and Reclaiming Association (ARRA). Basic asphalt recycling manual, federal highway administration. US Department of Transportation, Washington, D.C., 2001.

[4] Copeland A. Reclaimed asphalt pavement in asphalt mixtures: State of the practice. Office of Infrastructure Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101, Https://WwwFhwaDotGov/Publications/Research/Infrastructure/Pavements/11021/11021Pdf 2011;FHWA-HRT-1:55.

[5] Enieb M, Hasan Al-Jumaili MA, Eedan Al-Jameel HA, Eltwati AS. Sustainability of using reclaimed asphalt pavement: based-reviewed evidence. Journal of Physics: Conference Series 2021;1973:012242. https://doi.org/10.1088/1742-6596/1973/1/012242.

[6] Daniel JS, Lachance A. Mechanistic and Volumetric Properties of Asphalt Mixtures with Recycled Asphalt Pavement. Transportation Research Record: Journal of the Transportation Research Board 2005;1929:28–36. https://doi.org/10.1177/0361198105192900104.

[7] Eltwati AS, Enieb M, Al-Saffar ZH, Mohamed A. Effect of glass fibers and waste engine oil on the properties of RAP asphalt concretes. International Journal of Pavement Engineering 2021:1–12. https://doi.org/10.1080/10298436.2021.2001815.

[8] Eltwati A, Al-Saffar Z, Mohamed A, Rosli Hainin M, Elnihum A, Enieb M. Synergistic effect of SBS copolymers and aromatic oil on the characteristics of asphalt binders and mixtures containing reclaimed asphalt pavement. Construction and Building Materials 2022;327:127026. https://doi.org/10.1016/J.CONBUILDMAT.2022.127026.

[9] ELTWATİ A, ENIEB M, AHMEED S, AL-SAFFAR Z, MOHAMED A. Effects of waste engine oil and crumb rubber rejuvenator on the performance of 100% RAP binder. Journal of Innovative Transportation 2022;3:8–15. https://doi.org/10.53635/jit.1072888.

[10] Eltwati A, Mohamed A, Hainin MR, Jusli E, Enieb M. Rejuvenation of aged asphalt binders by waste engine oil and SBS blend: Physical, chemical, and rheological

properties of binders and mechanical evaluations of mixtures. Construction and Building Materials 2022;346:128441. https://doi.org/10.1016/j.conbuildmat.2022.128441.
[11] Antunes V, Freire AC, Neves J. A review on the effect of RAP recycling on bituminous mixtures properties and the viability of multi-recycling. Construction and Building Materials 2019;211:453–69. https://doi.org/10.1016/j.conbuildmat.2019.03.258.
[12] Izaks R, Haritonovs V, Klasa I, Zaumanis M. Hot Mix Asphalt with High RAP Content. Procedia Engineering 2015;114:676–84. https://doi.org/10.1016/j.proeng.2015.08.009.
[13] Valdés G, Pérez-Jiménez F, Miró R, Martínez A, Botella R. Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP). Construction and Building Materials 2011;25:1289–97. https://doi.org/10.1016/j.conbuildmat.2010.09.016.
[14] Mogawer WS, Austerman AJ, Bonaquist R, Roussel M. Performance Characteristics of Thin-Lift Overlay Mixtures. Transportation Research Record: Journal of the Transportation Research Board 2011;2208:17–25. https://doi.org/10.3141/2208-03.
[15] Behnood A. A review of the warm mix asphalt (WMA) technologies: Effects on thermo-mechanical and rheological properties. Journal of Cleaner Production 2020;259:120817. https://doi.org/10.1016/j.jclepro.2020.120817.
[16] Colbert B, You Z. The properties of asphalt binder blended with variable quantities of recycled asphalt using short term and long term aging simulations. Construction and Building Materials 2012;26:552–7. https://doi.org/10.1016/j.conbuildmat.2011.06.057.
[17] Kwon J, Seo Y, Yang J, Kaplan A. Field and numerical investigation of full depth reclamation with Portland cement in Georgia. Transportation Geotechnics 2021;27:100465. https://doi.org/10.1016/J.TRGEO.2020.100465.
[18] Rajib AI, Samieadel A, Zalghout A, Kaloush KE, Sharma BK, Fini EH. Do all rejuvenators improve asphalt performance? Road Materials and Pavement Design 2022;23:358–76. https://doi.org/10.1080/14680629.2020.1826348.
[19] Ziari H, Moniri A, Bahri P, Saghafi Y. Evaluation of performance properties of 50% recycled asphalt mixtures using three types of rejuvenators. Petroleum Science and Technology 2019;37:2355–61. https://doi.org/10.1080/10916466.2018.1550505.
[20] Sun D, Lu T, Xiao F, Zhu X, Sun G. Formulation and aging resistance of modified bio-asphalt containing high percentage of waste cooking oil residues. Journal of Cleaner Production 2017;161:1203–14. https://doi.org/10.1016/j.jclepro.2017.06.155.
[21] Dokandari PA, Kaya D, Sengoz B, Topal A. Implementing Waste Oils with Reclaimed Asphalt Pavement, 2017. https://doi.org/10.11159/icsenm17.142.
[22] Datt, R., Kumar, A. and Kumar, A. Waste cooking oil as a rejuvenating agent in aged bitumen. International Journal of Control Theory and Applications 2017;10:127–34.
[23] Zargar M, Ahmadinia E, Asli H, Karim MR. Investigation of the possibility of using waste cooking oil as a rejuvenating agent for aged bitumen. Journal of Hazardous Materials 2012;233–234:254–8. https://doi.org/10.1016/j.jhazmat.2012.06.021.
[24] Asli H, Ahmadinia E, Zargar M, Karim MR. Investigation on physical properties of waste cooking oil – Rejuvenated bitumen binder. Construction and Building Materials 2012;37:398–405. https://doi.org/10.1016/j.conbuildmat.2012.07.042.
[25] Ji J, Yao H, Suo Z, You Z, Li H, Xu S, et al. Effectiveness of Vegetable Oils as Rejuvenators for Aged Asphalt Binders. Journal of Materials in Civil Engineering 2017;29. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001769.
[26] Wen H, Bhusal S, Wen B. Laboratory Evaluation of Waste Cooking Oil-Based Bioasphalt as an Alternative Binder for Hot Mix Asphalt. Journal of Materials in Civil

Engineering 2013;25:1432–7. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000713.

[27] ASTM-D5. Standard Test Method for Penetration of Bituminous Materials. ASTM International, West Conshohocken, PA,1999, WwwAstmOrg 2020. https://doi.org/10.1520/D0005_D0005M-20.

[28] ASTM-D36. Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus). ASTM International, West Conshohocken, PA,1999, WwwAstmOrg 2020. https://doi.org/10.1520/D0036_D0036M-14R20.

[29] AASHTO T315. Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR). American Association of State Highway and Transportation Officials (AASHTO) 2020.

[30] ASTM D6648-08. Standard Test Method for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR). STM International, West Conshohocken, PA, WwwAstmOrg 2016. https://doi.org/10.1520/D6648-08R16.

[31] Ingrassia LP, Lu X, Ferrotti G, Canestrari F. Renewable materials in bituminous binders and mixtures: Speculative pretext or reliable opportunity? Resources, Conservation and Recycling 2019;144:209–22. https://doi.org/10.1016/J.RESCONREC.2019.01.034.

[32] ASTM D7175-15. Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer. ASTM International, West Conshohocken, PA, WwwAstmOrg 2015. https://doi.org/10.1520/D7175-15.

[33] Eltwati A, Al-Saffar Z, Mohamed A, Rosli Hainin M, Elnihum A, Enieb M. Synergistic effect of SBS copolymers and aromatic oil on the characteristics of asphalt binders and mixtures containing reclaimed asphalt pavement. Construction and Building Materials 2022;327:127026. https://doi.org/10.1016/j.conbuildmat.2022.127026.

[34] Hashim TM, Nasr MS, Jebur YM, Kadhim A, Alkhafaji Z, Baig MG, et al. Evaluating Rutting Resistance of Rejuvenated Recycled Hot-Mix Asphalt Mixtures Using Different Types of Recycling Agents. Materials 2022;15:8769. https://doi.org/10.3390/ma15248769.

[35] Li X, Wen H, Edil TB, Sun R, VanReken TM. Cost, energy, and greenhouse gas analysis of fly ash stabilised cold in-place recycled asphalt pavement. Road Materials and Pavement Design 2013;14:537–50. https://doi.org/10.1080/14680629.2013.779302.

[36] Sangiorgi C, Tataranni P, Simone A, Vignali V, Lantieri C, Dondi G. A laboratory and filed evaluation of Cold Recycled Mixture for base layer entirely made with Reclaimed Asphalt Pavement. Construction and Building Materials 2017;138:232–9. https://doi.org/10.1016/J.CONBUILDMAT.2017.02.004.

[37] Taherkhani H, Noorian F. Comparing the effects of waste engine and cooking oil on the properties of asphalt concrete containing reclaimed asphalt pavement (RAP). Road Materials and Pavement Design 2020;21:1238–57. https://doi.org/10.1080/14680629.2018.1546220.

[38] Aboelmagd AY, Khedr S, Moussa GS, Abdalla E-SM, Enieb M. Waste nanomaterial-modified asphalt for economic and sustainable pavement construction. Innovative Infrastructure Solutions 2022;7:144. https://doi.org/10.1007/s41062-021-00737-0.

[39] Liu Z, Sun L, Zhai J, Huang W. A review of design methods for cold in-place recycling asphalt mixtures: Design processes, key parameters, and evaluation. Journal of Cleaner Production 2022;370:133530. https://doi.org/10.1016/j.jclepro.2022.133530.

[40] Federal Highway Administration. User Guidelines for Waste and Byproduct Materials in Pavement Construction. Report No. FHWA-RD-97-148. National Asphalt Pavement

Association 5100 Forbes Boulevard Lanham, Maryland 20706-4413 1997.
[41] Faramarzi M, Kim Y, Kwon S, Lee K-WW. Evaluation of Cold Recycled Asphalt Mixture Treated with Portland Cement as Base-Layer Materials. Journal of Materials in Civil Engineering 2020;32. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003073.
[42] Meocci M, Grilli A, La Torre F, Bocci M. Evaluation of mechanical performance of cement–bitumen-treated materials through laboratory and in-situ testing. Road Materials and Pavement Design 2017;18:376–89. https://doi.org/10.1080/14680629.2016.1213506.
[43] ASTM D6926-20. Standard Practice for Preparation of Asphalt Mixture Specimens Using Marshall Apparatus. ASTM International, West Conshohocken, PA, WwwAstmOrg 2020.
[44] AASHTO M323. Standard Specification for Superpave Volumetric Mix Design. The American Association of State Highway and Transportation Officials, Washington, DC 2022.
[45] Easa SM. Superpave Design Aggregate Structure Considering Uncertainty: I. Selection of Trial Blends. Department of Civil Engineering, Ryerson University, Toronto, ON, Canada 2018;48.
[46] Diefenderfer BK, Boz I, Habbouche J, Jones D, Hand AJ. Development and Assessment of Rapid Tests for Construction of Asphalt-Treated Cold Recycled Pavements. Transportation Research Record: Journal of the Transportation Research Board 2020;2674:189–98. https://doi.org/10.1177/0361198120908867.
[47] ASTM D4402 / D4402M-15. Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer. STM International, West Conshohocken, PA, WwwAstmOrg 2015. https://doi.org/10.1520/D4402_D4402M-15.
[48] ASTM-D2172. Standard Test Methods for Quantitative Extraction of Asphalt Binder from Asphalt Mixtures. ASTM International, West Conshohocken, PA, WwwAstmOrg 2017.
[49] Institute AJMD. Asphalt Mix Design Methods 2015.
[50] Jiang J, Ni F, Zheng J, Han Y, Zhao X. Improving the high-temperature performance of cold recycled mixtures by polymer-modified asphalt emulsion. International Journal of Pavement Engineering 2020;21:41–8. https://doi.org/10.1080/10298436.2018.1435882.
[51] Xu G, Ma T, Fang Z, Huang X, Zhang W. The Evaluation Method of Particle Clustering Phenomena in RAP. Applied Sciences 2019;9:424. https://doi.org/10.3390/app9030424.
[52] Otieno MN, Kaluli JW, Kabubo C. Strength Prediction of Cold Asphalt Emulsion Mixtures Using the Maturity Method. Journal of Materials in Civil Engineering 2020;32. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003166.
[53] Kuchiishi AK, Vasconcelos K, Bariani Bernucci LL. Effect of mixture composition on the mechanical behaviour of cold recycled asphalt mixtures. International Journal of Pavement Engineering 2021;22:984–94. https://doi.org/10.1080/10298436.2019.1655564.
[54] ASTM D2726/D2726M-21. Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Asphalt Mixtures. ASTM International, West Conshohocken, PA, WwwAstmOrg 2021.
[55] Amouzadeh Omrani M, Modarres A. Emulsified cold recycled mixtures using cement kiln dust and coal waste ash-mechanical-environmental impacts. Journal of Cleaner

Production 2018;199:101–11. https://doi.org/10.1016/J.JCLEPRO.2018.07.155.

[56] Pi Y, Huang Z, Pi Y, Li G, Li Y. Composition Design and Performance Evaluation of Emulsified Asphalt Cold Recycled Mixtures. Materials 2019;12:2682. https://doi.org/10.3390/ma12172682.

[57] Tabaković A, McNally C, Fallon E. Specification development for cold in-situ recycling of asphalt. Construction and Building Materials 2016;102:318–28. https://doi.org/10.1016/j.conbuildmat.2015.10.154.

[58] Godenzoni C, Graziani A, Bocci E, Bocci M. The evolution of the mechanical behaviour of cold recycled mixtures stabilised with cement and bitumen: field and laboratory study. Road Materials and Pavement Design 2018;19:856–77. https://doi.org/10.1080/14680629.2017.1279073.

[59] Loizos A, Plati C. Ground penetrating radar as an engineering diagnostic tool for foamed asphalt treated pavement layers. International Journal of Pavement Engineering 2007;8:147–55. https://doi.org/10.1080/10298430601149528.

[60] Yang Y, Yang Y, Qian B. Performance and Microstructure of Cold Recycled Mixes Using Asphalt Emulsion with Different Contents of Cement. Materials 2019;12:2548. https://doi.org/10.3390/ma12162548.

[61] Betti G, Airey G, Jenkins K, Marradi A, Tebaldi G. Active fillers' effect on in situ performances of foam bitumen recycled mixtures. Road Materials and Pavement Design 2017;18:281–96. https://doi.org/10.1080/14680629.2016.1213486.

[62] ASTM D6925-15. Standard Test Method for Preparation and Determination of the Relative Density of Asphalt Mix Specimens by Means of the Superpave Gyratory Compactor. ASTM International, West Conshohocken, PA, WwwAstmOrg 2016.

[63] Kim Y, Lee H "David", Heitzman M. Validation of New Mix Design Procedure for Cold In-Place Recycling with Foamed Asphalt. Journal of Materials in Civil Engineering 2007;19:1000–10. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:11(1000).

[64] Kim Y, Lee HD. Influence of Reclaimed Asphalt Pavement Temperature on Mix Design Process of Cold In-Place Recycling Using Foamed Asphalt. Journal of Materials in Civil Engineering 2011;23:961–8. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000274.

[65] Saleh MF. Effect of rheology on the bitumen foamability and mechanical properties of foam bitumen stabilised mixes. International Journal of Pavement Engineering 207AD;8:99–110.

[66] Wirtgen GmbH. http://www.wirtgen.de/en/products/cold-recyclers/wlb-10-s/ 2015.

[67] Diab A. Binder Rheology and Moisture Susceptibility of Nano-sized Hydrated Lime-Modified Foamed Warm Mix Asphalt. Ph.D. thesis, University of Aswan, Egypt, 2014.

[68] Fang X, Winnefeld F, Lura P. Precipitation of anionic emulsifier with ordinary Portland cement. Journal of Colloid and Interface Science 2016;479:98–105. https://doi.org/10.1016/J.JCIS.2016.06.042.

[69] Afonso ML, Dinis-Almeida M, Pereira-De-Oliveira LA, Castro-Gomes J, Zoorob SE. Development of a semi-flexible heavy duty pavement surfacing incorporating recycled and waste aggregates – Preliminary study. Construction and Building Materials 2016;102:155–61. https://doi.org/10.1016/J.CONBUILDMAT.2015.10.165.

[70] Apaza Apaza FR, Rodrigues Guimarães AC, Marcos Vivoni A, Schroder R. Evaluation of the performance of iron ore waste as potential recycled aggregate for micro-surfacing type cold asphalt mixtures. Construction and Building Materials 2021;266:121020. https://doi.org/10.1016/J.CONBUILDMAT.2020.121020.

[71] Jiang J, Zhang Z, Dong Q, Ni F. Characterization and identification of asphalt mixtures

based on Convolutional Neural Network methods using X-ray scanning images. Construction and Building Materials 2018;174:72–80. https://doi.org/10.1016/J.CONBUILDMAT.2018.04.083.

[72] Zhu J, Ma T, Fang Z. Characterization of agglomeration of reclaimed asphalt pavement for cold recycling. Construction and Building Materials 2020;240:117912. https://doi.org/10.1016/J.CONBUILDMAT.2019.117912.

[73] Lin J, Huo L, Xu F, Xiao Y, Hong J. Development of microstructure and early-stage strength for 100% cold recycled asphalt mixture treated with emulsion and cement. Construction and Building Materials 2018;189:924–33. https://doi.org/10.1016/J.CONBUILDMAT.2018.09.064.

[74] Yang W, Ouyang J, Meng Y, Han B, Sha Y. Effect of curing and compaction on volumetric and mechanical properties of cold-recycled mixture with asphalt emulsion under different cement contents. Construction and Building Materials 2021;297:123699. https://doi.org/10.1016/J.CONBUILDMAT.2021.123699.

[75] Castaneda FA. Hveem Mix Design and Engineering Properties of Cold In-Place Recycling Mixtures. University of Nevada, Reno.; 2018.

[76] ASTM C117-17. Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing. ASTM International, West Conshohocken, PA, WwwAstmOrg 2020.

[77] ASTM C136-06. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International, West Conshohocken, PA, WwwAstmOrg 2015.

[78] ASTM D244-09. Standard Test Methods and Practices for Emulsified Asphalts. STM International, West Conshohocken, PA, WwwAstmOrg 2017.

[79] Zhu C, Zhang H, Guo H, Wu C, Wei C. Effect of gradations on the final and long-term performance of asphalt emulsion cold recycled mixture. Journal of Cleaner Production 2019;217:95–104. https://doi.org/10.1016/j.jclepro.2019.01.264.

[80] ASTM D1075-07. Standard Test Method for Effect of Water on Compressive Strength of Compacted Bituminous Mixtures. ASTM International, West Conshohocken, PA, WwwAstmOrg 2011.

[81] ASTM D6931. Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures. ASTM International, West Conshohocken, PA, WwwAstmOrg 2017.

[82] AASHTO T 324. Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures. American Association of State Highway and Transportation Officials (AASHTO) 2019.

[83] ASTM D6927-15. Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures. ASTM International, West Conshohocken, PA, WwwAstmOrg 2022.

[84] ASTM D4123-82. Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures (Withdrawn 2003). STM International, West Conshohocken, PA, WwwAstmOrg 1995.

[85] Niazi Y, Jalili M. Effect of Portland cement and lime additives on properties of cold in-place recycled mixtures with asphalt emulsion. Construction and Building Materials 2009;23:1338–43. https://doi.org/10.1016/j.conbuildmat.2008.07.020.

[86] Head RW. An informal report of cold mix research using emulsified asphalt as binder. In: Proceedings of the AAPT, 1974, p. 110–31.

[87] Dong S, Wang D, Hao P, Zhang Q, Bi J, Chen W. Quantitative assessment and mechanism analysis of modification approaches for cold recycled mixtures with asphalt emulsion. Journal of Cleaner Production 2021;323:129163. https://doi.org/10.1016/j.jclepro.2021.129163.

[88] Gandi A, Cardenas A, Sow D, Carter A, Perraton D. Study of the impact of the compaction and curing temperature on the behavior of cold bituminous recycled materials. Journal of Traffic and Transportation Engineering (English Edition) 2019;6:349–58. https://doi.org/10.1016/j.jtte.2019.03.002.

[89] Santos J, Flintsch G, Ferreira A. Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. Resources, Conservation and Recycling 2017;116:15–31. https://doi.org/10.1016/j.resconrec.2016.08.025.

[90] Offenbacker D, Saidi A, Ali A, Mehta Y, Decarlo CJ, Lein W. Economic and Environmental Cost Analysis of Cold In-Place Recycling. Journal of Materials in Civil Engineering 2021;33. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003610.

[91] AASHTO. Practical Guide to Cost Estimating. American Association of State Highways and Transportation Officials Washington DC, USA 2013.

[92] CAA. Road Rehabilitation Energy Reduction Guide for Canadian Road Builders. Canadian Construction Association, Ontario, Canada 2015.

[93] Zarrinkamar BT, Modarres A. Optimizing the asphalt pavement cold in-place recycling process containing waste pozzolans based on economic-environmental-technical criteria. Journal of Cleaner Production 2020;242:118505. https://doi.org/10.1016/j.jclepro.2019.118505.

[94] Bouraima MB, Zhang XH, Rahman A, Qiu Y. A comparative study on asphalt binder and mixture performance of two traffic lanes during hot in-place recycling (HIR) procedure. Construction and Building Materials 2019;223:33–43. https://doi.org/10.1016/j.conbuildmat.2019.06.201.

[95] Ali H, McCarthy LM, Welker A. Performance of hot in-place recycled Superpave mixtures in Florida. Construction and Building Materials 2013;49:618–26. https://doi.org/10.1016/J.CONBUILDMAT.2013.08.043.

[96] Roads B. How the HIP asphalt recycling process can save you money. James Informational Media, Inc 2000;70.

[97] Asphalt pavement Association of Mitchigan. Reclaimed Asphalt Pavement (RAP), Microsoft PowerPoint - RAP 2012 LRW final. 2012.

[98] ASTM D4887/D4887M-11(2021)e1. Standard Practice for Preparation of Viscosity Blends for Hot Recycled Asphalt Materials. STM International, West Conshohocken, PA, WwwAstmOrg 2021.

[99] Keith W. Anderson, Mark Russell, Jeff S. Uhlmeyer JD, Weston CJ and J. Long-term performance of a hot in-place recycling project final report. 2016.

[100] Garret D. Reeder, Dale S. Harrington, Michael E. Ayers WA. Guide to Full-Depth Reclamation (FDR) with Cement. Portland Cement Association 2017:104.

[101] Ohio Department of Transportation. Special Provision Full Depth Reclamation (FDR) Chemical Stabilization. 2010.

[102] California Department of Transportation. Standard Specification 30-4 Full Depth Stabilization - Cement. 2018.

[103] New York Department of Transportation. Geotechnical Engineering Manual: Design and Construction Guideline for Full Depth Reclamation of Asphalt Pavement. 2015.

[104] Tolbert JC. Effect of High Percentages of Reclaimed Asphalt Pavement on Mechanical Properties of Cement-Treated Base Material. M.S. Thesis. Brigham Young University, 2014.

[105] Abdalim AMK. Pavement full-depth reclamation(FDR) technology. Master of Engineering, Civil Engineering Department, Assiut University, 2022.