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RECYCLING TOWARD SUSTAINABLE PAVEMENT DEVELOPMENT:END-OF-LIFE CONSIDERATIONS IN ASPHALT PAVEMENT

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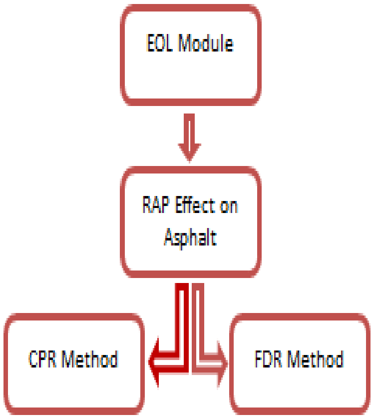
Graphical abstract



Abstract

As quality aggregate sources are depleted, there is a growing importance given to incorporating recycled co-products and waste materials (RCWMs) in new and rehabilitated pavements. An ideal goal would be using recycled materials to create long-lived, well-performing pavement and then being able to use those materials again at the end of their life to create new pavement, thereby effectively achieving a zero-waste highway construction stream. This would not only produce distinct cost advantages, but it would also significantly reduce energy consumption and greenhouse gas (GHG) emissions and eliminate the need for landfill disposal. Drawing from ISO standards and practices, this article reviews the recycling methods and definitions associated with the End-of-Life (EOL) phase and present various EOL considerations for asphalt pavements and the associated challenges to quantify EOL contribution in the pavement life cycle.

Keywords: End- of- life (EOL) module, sustainable development, recycled co-product and waste material (RCWM), central plant recycling (CPR), full-depth reclamation (FDR)

1.0 INTRODUCTION

When pavement reaches its end-of-life, it may remain in place and be reused as part of the supporting structure for new pavement, recycled, or removed and land filled. Each has economic and environmental costs, as do the more visible stages of the pavement life cycle (e.g., material module, initial pavement construction, and use phase). Therefore, end-of-life activities can affect sustainability factors, such as waste generation and disposition, air and water quality, and materials use. They must be considered in a comprehensive life cycle assessment (LCA).

Asphalt pavements are commonly recycled and reused as construction materials [1]. Chesner *et al.* [2] provided a description of reclaimed asphalt pavement (RAP) and its reuse in highway applications. There was a 22% increase in the use of RAP in 2012 compared to 2009 in the United States of America [3]. These recycled materials have several uses: reuse in new asphalt mixtures; aggregates in base layers; and fill, riprap, or ballast. Figure 1 shows a distribution of the use of recycled asphalt materials.
Infrastructure professionals, such as urban planners, architects, and engineers, have started to consider the application of zero-waste or closed-loop concepts. ISO 14044 defines a closed-loop as a

product system in which a material is recycled back into it, and an open loop as a system in which material from one product system is recycled into a different product system [4]. The measurable value left in recycled pavement can make it reusable multiple times [5]. Therefore, pavement recycling is more analogous to a closed-loop for its potential for numerous reuses.

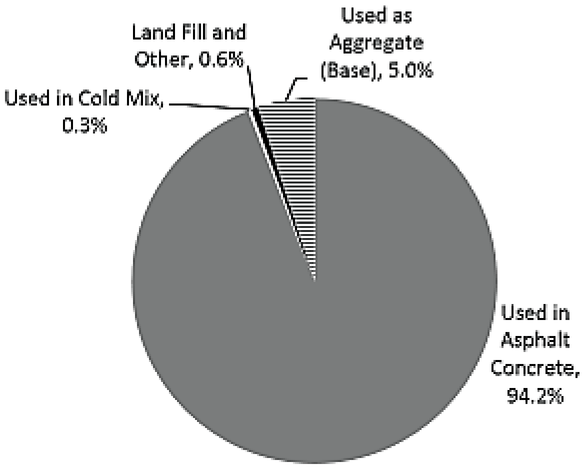


Figure 1 Recycling and reuse statistics of asphalt materials [5].

1.1 Economic and Environmental Considerations of EOL Options

One of the compelling approaches to enhance sustainable pavement development is utilizing material at the end of life cycle (EOL). In order to evaluate impacts of recycling in the EOL completely, both the economic and environmental aspects must considered. For instance, material transport could profoundly affect the total costs and it sometimes as the same price as raw material transport to construction site [6]. Crucial factors same as materials' quality, landfill costs, on-site/off-site technology, transportation and application should be noted in analysis.

- *Material quality* – determining of originality, procedure, stockpiling and local specification of recycled material are the vital application. The distinctive concrete asphalt pavement projects need of utilizing different recycled material base on use in surface or underground layers.The potential pollution hazard by using recycled could minimize its utilization and application.
- *Landfill costs - By disposal recycled material numeral costs need to figure.* Landfilling contains distinctive costs same as destruction, deliver, and tipping fees. Horvath [6] expressed that tipping fees could variance $10 to $70 per each ton of recycled material even in small distance. Nowadays, it should be note that reducing number of landfill is imperative issue.
- *In-site/off-site Technology* – This can be a key serving to decidefor on-site and off-site recycling. This contains of the development construction tools and equipment which utilized for on-site recycling, such as cold in-place recycling, hot in-place recycling, and full-depth reclamation. Also, if the pavement is recycled in a central plant, the environmental costs include demolition at the job site, crushing, screening, and stockpiling at the plant.
- *Transportation* – Delivery can have the astounding effect on the environmental burden for recycled materials. This circle of transport can be from site to a landfill, from site to a central plant for processing, or from the plant back to the job site.
- *Application* – Recycled asphalt can be reused in pavements as base layers or surface layers, in addition to embankments, fills, and scores of other potential uses.

2.0 LITURATURE REVIEW

Since the energy crisis of the 1970s, asphalt pavement recycling has played a significant role in the pavement rehabilitation and preservation strategies of highway agencies. Agencies are interested in reducing energy consumption, material and transportation costs, and GHG emissions seek out effective pavement recycling strategies.

Babashamsi *et al.* [7] stated that the end of life module (EOL) has been abounded by numerous of the past LCA studies (just considered 4 out of 30). The pavement can be landfilled, recycled, or covered and turned into a steady base layer for following pavement structure. Every pavement needs a specific approach for evaluating the environmental impact. Ranjendran and Gambatese [8] guaranteed that EOL represents more than 50 percent of the overall aggregate in waste process management during the life-cycle of a pavement. Likewise, by recycling the human toxicity and ecology toxicity, and additionally all other environment impact like as global warming potential (GWP), energy consumption, eutrophication, acidification, and tropospheric ozone formation will be diminished [9].

to concentrate on the level of waste management system and expending resources throughout the world, the 'recycling' activity of the EOL module can be accounted as a high impact record to develop the usage of recycled materials in next pavement projects and, in this way, resource assurance for next generation and this is the major meaning of sustainability. Asphalt pavement recycling is possible through central plant or in-place recycling techniques (full-depth reclamation).

2.1 Recycling and Asphalt Road Materials

Onevital source of aggregate and asphalt binder for asphalt pavement projects is RAP. RAP can be utilized as a swap for raw aggregate base, which does not take full advantage of the potential contribution of the asphalt coating the aggregate as a binder. Recycled materials generally should be utilized for the highest use which would be first as trade for virgin asphalt and aggregate in new asphalt concrete, followed by use in recycled cold-mix materials, followed by use as aggregate base or aggregate in concrete. Due to the impact of petroleum acquisition and refining the asphalt binder in asphalt concrete conveys a significant part of total environmental impact. Utilization of RAP in asphalt concrete replaces not only raw aggregate, but the RAP binder is reusedas binder, at least in part, thereby reducing the amount of virgin binder needed in the new asphalt concrete. Thereby, RAP use in new asphalt concrete decreases the requirement for virgin asphalt and aggregate, both non-renewable and finite materials, making asphalt concrete the astounding usable pavement.

In the USA, in 2011, the measure of RAP utilized in asphalt mixtures was 66.7 million tons, which it is increased 19 percent compare to 2009 (56 million tons) and about a 7 percent expansion over 2010 (62.1 million tons). By assuming 5 percent liquid asphalt in RAP, this represents approximately 3.6 million tons , of virgin asphalt binder moderated, or about 12 percent of the total binder utilized in 2011 [10].

Because residual binder, asphalt binder in RAP, has been oxidized through previous heating in the mixer and its atmospheric exposure during service is generally stiffer and more fragile than virgin asphalt. Although the aged residual asphalt binder will harden the new mixture and generally enhancing rutting resistance, conceivably expanding the inclination for top-down cracking when utilized as a part of surface mixtures unless it is well managed through specifications. The stiffer, aged residual binder in RAP can help reduce bending and tensile strains that contribute to bottom-up cracking when used in thicker layers below the surface. The ability to control particle size and avoid segregation during mixing with virgin materials in an asphalt plant is largely dependent on whether the RAP is sized, or fractionated, and binned into various consistent size gradations [11, 12]. Controlling particle size is more difficult during in-place mixing processes.

2.1.1 Environmental and Economic Impact of RAP

Proponents of asphalt cite resource conservation recommend to utilize high RAP content and reduce waste management. However, it is necessary to corroborate such claims in a quantified way over the pavement life cycle. Horvath [6], Ventura *et al.* [9], and more recently, Aurangzeb and Al-Qadi [13] and Aurangzeb *et al.* [14] discussed the environmental benefits and trade-offs of using RAP in pavements from a pavement life-cycle perspective.

Pavements incorporating RAP should be evaluated using life cycle cost analysis (LCCA) and LCA without neglecting the material and maintenance modules. For example, for asphalt binder mixtures with 30, 40, and 50% RAP, LCCA found a net savings up to $58,000/km, whereas for asphalt mixtures with 30 to 50% RAP, LCA found energy savings of 800 to 1400 MBTU and GHG reductions of 70 to 117 ton [13]. However, considering of inherent properties of recycled pavement materials contends that the pavement with recycled mixtures may decay quicker in the field than pavements with less (or without any) RAP. The possible substandard performance of recycled mixtures will require more maintenance and rehabilitation supports, therefore balancing the economic and environmental advantages of utilizing RAP. Figure 2 illustrates the costs and emissions as the percentage of RAP increases. An “optimum performance level” refers to the point at which the economic and environmental benefits of using RAP counterbalance the project costs and environmental burden incurred from an increased frequency of maintenance and rehabilitation activities.

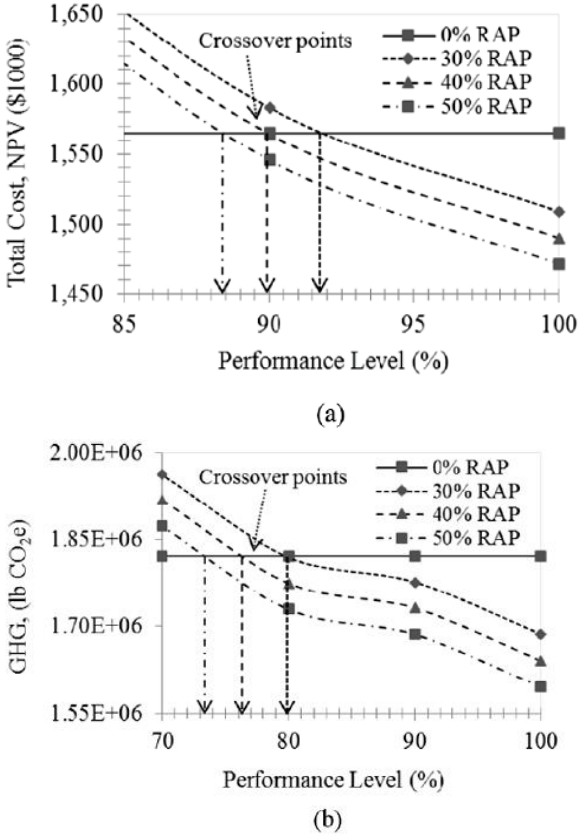


Figure 2 (a) total cost and (b) GHG emissions optimal performance levels [14].

One environmental concern of RAP use is leachate when RAP is stockpiled, landfilled, or incorporated in a surface layer vulnerable to water infiltration. Investigating this issue, Brantley and Townsend [15] concluded that RAP samples in the study did not produce hazardous waste nor leach chemicals greater than the amount typical groundwater standards allow. Horvath [16] reported average metal concentrations for various recycled and co-product materials used in construction, including RAP. The materials only exceeded the hazardous limits for two metals (barium and lead) out of the 15 examined. Legret *et al.* [17] also concluded that insignificant leaching occurred from RAP.

2.2 Central Plant Recycling

Central plant recycling (CPR) is the process of producing hot or cold asphalt mixtures in a central plant by combining virgin aggregates, new asphalt binder, recycling agents, and RAP. Regularly RAP is processed through cold milling or by ripping and demolishing of on lays pavements and then delivered to asphalt plants. RAP from various sources are normally kept in different stockpiles, and is usually separated into two, or sometimes three, different sizes at the asphalt plant.

Hot central plant recycling (HCPR) employs heat transfer to soften RAP for mixing. Consequently, RAP's moisture content should be kept to a practical minimum; otherwise, the heat is expended on turning moisture into steam, rather than softening RAP. Heat transfer, carried out by overheating the virgin aggregates before introducing RAP into the drum, may lead to additional fuel and energy use, which could offset the economic and environmental benefits of using RAP.

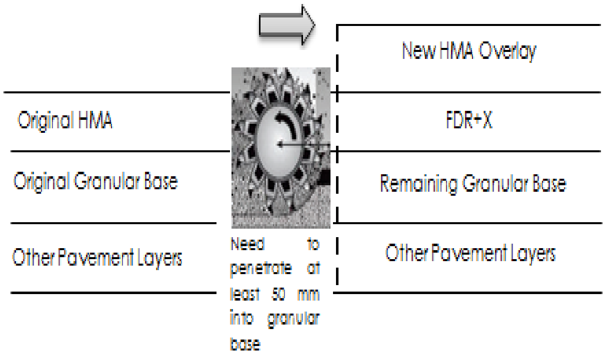
On the other hand, cold central plant recycling (CCPR) combines RAP with an emulsified asphalt/recycling agent without heat; new aggregates are added as needed. Although not a common practice [2, 3], the mixture can be used for surface, base, or sub-base courses. ASTM D4215 contains specifications for cold plant recycled mixtures.

2.2.1 Economic and Environmental Impact of CPR

Processing and fractionating RAP on the central plant expands product unity and, consequently, produces further consistent asphalt concrete containing RAP. However, there are charges involved in process and fractionate RAP. The amount of RAP that finally finishes up in a given fractionated stockpile is typically a function of the confirm material and therefore the sizes designated for fractionation. This, in turn, dictates how tons every fractionated size is available to be used in the new asphalt concrete. Al-Qadi *et al.* [18] illustrated a complete review of RAP usage in central plant recycling. Plant production of mixtures with high RAP leads to high dust contents and challenges in assessing determinations. Dust control is an essential problem with the use of RAP in a central plant facility, while only a few of them are equipped to correctly waste dust or even fewer have an outlet for that dust although the plant is capable of wasting it [5].Without having the capacity to address the expanding dusts, the utilization of a clean/washed aggregate material becomes vital in order to accomplish dust control.

2.3 Full-Depth Reclamation

Full-depth reclamation (FDR) is a technique in which the full thickness of the existing asphalt pavement and a predetermined portion of the underlying materials (e.g., base, sub-base, and subgrade) are uniformly pulverized and blended into a homogeneous material. After being mixed with or without additional binders, additives, and water, the pulverized material is laid, graded, and compacted to provide an improved base layer for the final surface layers. Full-depth reclamation can be performed through single, two-, or multi-unit trains [19]. The FDR trains may include combinations of a reclaimer (milling, reclaimer, and stabilizer), pugmill mixer/paver, or a portable crushing and screening unit [20] as it shown in Figure 3.



X could be: No stabilizer, Foamed asphalt+cement, Cement or Asphalt emulsion

Figure 3 Full-depth reclamation trains.

FDR recycles thicker pavement layers and helps address specific problems rooted in different layers; this distinguishes from other commonly used rehabilitation techniques, such as cold and hot in-place recycling. FDR can recycle pavement depths up to 12 inches (305 mm), with depths of 6 to 9 inches (152 to 229 mm) being more common [21, 22]. Pulverization, stabilization and overlay or surface treatments are three basic components of FDR processing [5].

- *Pulverization* – Pulverization is the principle phase of the FDR procedure where existing HMA and part of the granular layers are changed into unity granular material later with an objective degree that can be utilized as base layer. Once the layers are pulverized, a compacted base layer can be acquired by including appropriate moisture.

- *Stabilization* – Additives and stabilizers are regularly added to the pulverized materials to enhance the quality and structural capacity of the compacted layers. Stabilization can be classified into four groups [21]. Asphalt stabilization which is utilizing foamed asphalt binder or asphalt emulsion [23, 24, 25, 26].Mechanical stabilization which includes the consolidation of imported granular materials such as RAP/RCA or crashed aggregate to accomplished desired density, compaction and gradation. Chemical stabilization by including added substances same as fly ash, calcium chloride, magnesium chloride, lime, and Portland cement. Combination of asphalt and chemical additives is also a probability to enhance the properties of recycled layers.
- *Overlay or Surface Treatment* – A structural asphalt concrete overlay is usually utilized as the last wearing surface for a FDR project, in spite of several of surface treatments (chip seal, microsurfacing, slurry seal) may also be set.

Table 1 shows candidate pavement, advantages and limitations FDR projects.

Table 1 FDR advantages, candidate and limitations.

Summary	Description
Candidates Pavements	-Longitudinal and traverse cracking. -Poor ride quality. -Deformation problems. -Raveling and potholes problems. -Inadequate structural capacity.
Advantages	-Significant structural enhancement. -Most pavement distresses can address. -Increase ride quality. - Decrease energy use and emission. -correct smoothness deficiencies.
Limitations (not recommended)	-High volume roads (>20,000 ADT) -High percentage of trucks. -Areas with drainage problems. -High plasticity soils can lead to swelling.

2.3.1 Economic and Environmental Impact of FDR

ARRA [21], Stroup-Gardiner [22] and Wirtgen [23] are several detailed express references which documented comprehensive practice for FDR construction. At the same time, the successful execution and performance of FDR projects has been organized in the previous literature, same as Minnesota [27], Canada [28], Georgia [29], Nevada [30] and Indiana [31]. Some major potential benefits of FDR are conservation of virgin materials; reduction in the cost of pavement preservation, maintenance, and rehabilitation; reduce lane closures, fuel consumption, and mitigate emissions. These potential benefits can only be realized when the impact over the complete pavement life cycle is considered [5].Choose a proper project, mixture design, the also choose of proper added substance for the project, and effective compaction are all crucial factors to viable development of FDR construction.

- *Project Selection* – Recognizing key points of appropriate FDR project interest and critical details same as traffic, roadway geometry and features, and the ability of the existing pavement structure to support the equipment recycling train are important factors. The absence of project determination criteria was a powerful factor limiting the utilization of in-place recycling techniques [22]. Ordinary utilized undertaking choice criteria incorporate pavement condition (distress type and severity, ride quality), pavement thickness, roadway geometry, and identification of the required surface type for structural capacity, the prevention of moisture infiltration, and secure from thermal cracking.
- *Mixture Design* – A mixture design is needed for every FDR project. However, a uniform mixture design could be inconceivable due to the design relies on the properties of the in situ pulverized materials, which is regularly variable. The definitive target of mixture design is to assess the quantity and type of additive, water, and compactive effort. A standard mixture design specification does not presently exist for FDR mixtures, but guidelines have been developed by some states and agencies to aid the development of good quality FDR layers [32, 33]. Sieve analysis, extraction for binder content, soil plasticity, moisture susceptibility, critical low temperature cracking, resilient modulus, and triaxial compressive strength tests are usually conducted as part of the mixture design process. Material assessment is essentially concentrated on the wet and dry strength of FDR mixtures and determination of the compaction curve for optimum moisture and additive content at a specified curing time. Compaction equipment and techniques and curing times can also vary depending on the additives and in situ climatic conditions.
- *Additives* – The cost adequacy of added substances can change based on the characteristics of the project. However, one study stated that emulsion, cement, or a combination of both enhance moisture susceptibility of FDR mixtures [34]. The same study demonstrated that emulsion-lime blendemerges to be more cost-effective than water, emulsion, and cement stabilization. The important issue for stabilized layers is the categorization of the mixtures as “improved granular materials” or as bound materials such as HMA. The difference between two materials types manages the mixture design process as testing needed will fluctuate for every type of materials. Depending on the sort and amount of added substances, FDR mixtures can span a range of material behaviour from very stiff

(highly cemented) to very flexible (high emulsion content).

- *Compaction* – The significance of compaction and accomplishing target density is as important as selecting the perfect sum and type of additive. Mallick *et al.* [34] accentuate the determination of design number of gyrations and accomplishing the target density in the field. It was accounted that 97 percent of the laboratory density or 92 percent to 98 percent of the theoretical maximum specific gravity is appropriate for extensive variety of FDR mixtures [19].

3.0 RECOMENDATIONS AND DISCUSSION

Table 2 summarizes some general approaches to improving sustainability with regard to pavement recycling at the end of its life as well as the associated environmental benefits and trade-offs.

- Few asphalt plants are equipped with positive dust control (PDC) systems. A PDC system allows the producer to "waste dust" by returning less dust than is generated to the mixture. Then, the system accounts for the aggregate weight change and add the "correct" amount of virgin binder. Other energy efficient technologies should be explored.
- Improvement in the initial quality of paving materials and construction will increase performance and overall pavement life. The latter will reduce the total cost of pavement and number of recycling phases, thereby directly affecting the emissions of the total recycling process.
- The characteristics of recycled asphalt concrete materials, including those from plant and hot in-place recycling, differ from that of the original materials. The former usually exhibit relatively high stiffness due to the aged binder. Effective rejuvenators are needed to reduce their brittleness, a characteristic that also affects the fatigue and thermal cracking features of new pavement made from recycled materials. Using an optimized amount of a suitable rejuvenator would increase pavement life and thereby reduce life-cycle costs, its effect on the environment, and number of recycling phases. However, the upstream environmental effects of any rejuvenator or softening agent must also be considered.
- It is important to develop a mixture formula of asphalt concrete with RAP that meets the design volumetric, which would necessitate RAP fractionation. The latter requires the management of multiple stockpiles. This would achieve the initial mixture quality that would result in extended performance. In addition, to reduce energy costs of RAP processing, RAP stockpiles should be covered to prevent exposure to moisture.
- It is critical to use the proper type and amount of additives or stabilizers. Geotechnical inspection of the granular materials' in situ properties should inform the selection. This strategy may have a minimal effect on the environmental burden of the construction and material procurement phase; however, the expected improvement in performance and service life of FDR can offset the initial environmental burdens and costs.
- The type and thickness of an asphalt overlay can have a considerable effect on the environmental burden of initial construction. Moreover, proper placement can protect the recycled layers from weathering and slow down the deterioration rate. LCCA and LCA can be employed to identify the potential benefits of different structural overlay alternatives.
- Similar to any other highway construction work, construction quality is critical to the long-term performance of recycled pavements made with FDR. Inexperienced contractors and the relative complexity of FDR jobs, among others, represent risk factors. Stringent quality assurance protocols are critical to improve the long-term performance of pavements constructed with FDR.
- Shortage of mixture designs, details, and guidelines for select the project are a portion of the obstructions for FDR applications.
- EOL considerations in the life-cycle assessment consist of uncertainty which it is a hindrance for LCA evaluation. Due to this uncertainty, pavements are not generally given credits for producing recyclable materials at the end of pavement life cycle.
- The execution of in-place recycling that incorporates cold in-place and hot in-place recycling in addition to FDRis relatively low. In-place recycling is less than 50 lane miles (80 lane km) in the United States annually. However, central plant recycling is exceptionally regular.

Table 2 Approaches for improving sustainability of asphalt pavement recycling for pavement sustainability [5].

Asphalt Pavement Recycling Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Increase Central Plant Recycling Rate of Pavements	Improve plant technology (including heating time, positive dust control, double barrel etc.)	Requires initial capital investment for the producer. Can potentially reduce pavement production costs.	Can reduce GHG emissions if transportation burden will not offset.	Preserves virgin natural sources. Reduces need for landfills.
	Increase initial quality of pavement products and construction.	Can increase initial costs but may decrease life-cycle costs.	Can increase material production energy use but overall life-cycle energy and emissions may reduce.	Decline in natural resources.
	Use softening agents or rejuvenators.	Can increase material production costs.	Can reduce GHG emission in overall life cycle if pavement quality is improved.	Preserves virgin natural sources. Reduces need for landfills.
	Maintain and manage RAP stockpiles (reduce moisture, fractionation).	Can increase material production costs slightly but may decrease life-cycle costs.	Can increase material production energy use but overall life-cycle energy and emissions may reduce.	Preserves virgin natural sources. Reduces need for landfills.
Increase In-Place Recycling Rate of Pavements	Use the proper type and amount of additive or stabilizers.	Can increase material production costs but may decrease life-cycle costs.	Life-cycle energy and emissions may reduce.	Preserves virgin natural sources. Reduces need for landfills.
	Use structural asphalt overlays to improve weathering, cracking and fatigue resistance.	Can increase material production costs but may decrease life-cycle costs.	Life-cycle energy and emissions may reduce.	Preserves virgin natural sources. Reduces need for landfills.
	Develop standards for mixture design and QA to improve quality.	No costs.	Life-cycle energy and emissions may reduce since the quality is improved.	Preserves virgin natural sources. Reduces need for landfills.

4.0 CONCLUSION

This article expressed the EOL module of the pavement, especiallyconcentrating on recycling. Reclamation and recycling can lead toconsiderable cost savings and environmental impact decrease over the utilization of virgin materials when the technology (partial-depth recycling, full-depth reclamation) is appropriatelychosen, designed, and constructed. Continued evaluation and eventual adoption of a zero-waste strategy for all reconstruction projects should be considered. It has the primary benefit of reusing all of the existing pavement materials.However, it may also adversely influence the ability to completely use RAP containing the added substances in future asphalt concrete. Thus, these materials ought to be utilized where they givecritical expansions in execution. Also implementing it will require innovative equipment and approaches to ensure effective recovery and recycling. In addition, to minimize the recycled material's transportation cost and environmental impact, innovative equipment and processes thatrecycle the pavement completely in place should be considered.Recycled materialshave demonstrated to be at least equivalent to new materials in terms of quality, when appropriately designed. The quality of the recycled material stays a challenge for the pavement using recycled materials. The significant question with pavement recycling is: how many times can a pavement be recycled beforelosing the inherent properties?

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