

Development of Asphalt pavement Recycling Method for Road Maintenance and Construction in Ethiopia

By

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Abstract

Ethiopia is a landlocked country where the road network is of paramount importance as it carries over 90% of freight and people movement. Cognizant of this, the government launched a Road Sector Development Program (RSDP) in 1997 and spent over 525billion ETB (9.53 billion USD) for rehabilitation, upgrading and construction over 25 years. Seventy percent of the expenditure was on asphalt roads. Many of the roads constructed, upgraded or rehabilitated since the beginning of the RSDP are reaching the end of their design life and are creating a significant backlog in road maintenance works due to budget constraints and capacity limitations. Due to the lack of maintenance and increase in traffic, many roads need major rehabilitation. Conventional mill and overly may not be feasible considering the urgency of rehabilitating these roads and there is a need to reduce costs and conserve natural materials to improve sustainability and reduce environmental impact. It is considered that these benefits can be achieved by reusing old asphalt pavement. Accordingly, systematic review of the literature combined with suitability criteria was used to select the most appropriate recycling method. Using Analytical Hierarchy Process the criteria were evaluated and those related to cost effectiveness, Ease of application, environment, and energy conservation are more important in evaluating recycling methods. The result indicated that cold recycling methods are more favorable than hot recycling. It is also found out that as the Reclaimed Asphalt Pavement (RAP) amount used increases an average of 27%cost saving is obtained for RAP 20% to 90%used in HMA mix. The maximum amount of cost saving was 49% obtained for 90% RAP. Economic analysis indicated that saving on total transport cost does not vary for different climatic zones (Semi-arid, Sub-humid and Tropical-humid), however, they showed different pavement deterioration trends.

Key Words: Systematic review, Recycling, Asphalt, Pavement rehabilitation, RAP materials.

Dedication

To my Wife

Nigest, and

my children

Nardos, Hanna and Mikiyas

For your continuous support and patience

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1 INTRODUCTION

1.1 Background

A road is the most important infrastructure that provides access to rural and urban areas. Ethiopia is a landlocked country where the road network is of paramount importance as it carries over 90% of freight and people movement. Being aware of this importance, the government launched a Road Sector Development Program (RSDP) in 1997 and spent over 525 billion ETB (approximately 9.53 billion USD) for rehabilitation, upgrading and construction over 25 years. During this period, 171,814 km of the roads were constructed, upgraded or rehabilitated. 76.4% of the expenditure (402 billion ETB, 7.29 billion USD) was on asphalt roads. An increasing number of roads constructed in the early part of the RSDP are beginning to show significant deterioration as they are reaching the end of their design life. With increasing budget constraints, a significant backlog in road maintenance and rehabilitation is developing. Due to a lack of maintenance and an increase in traffic, many of the roads are reaching a point where maintenance will be inadequate; they will require major rehabilitation and some will need reconstruction.

Meeting the rehabilitation demand for these roads using conventional methods is challenging, as on average for the last ten years, the annual budget allocation from the Road Fund office was about 50% of the required budget. In addition to this, aggregate production has been getting difficult due to right-of-way related issues and import restrictions of bitumen owing to financial constraints. These challenges are rapidly escalating the cost of pavement construction.

Based on data from the last 25 years assessment of the RSDP, on average 650km of Trunk and Link roads have been rehabilitated and upgraded annually. Considering the same data and assuming an annual average for the next ten years it is estimated that 2,275,000m^3 of aggregate will be required annually considering 7m wide pavement and 5cm thick asphalt with 5% bitumen content. If we recycle 25% of the pavement material, we can save the production of 540,312m3of crushed aggregate annually. Therefore, it is possible to save more than 5.4million m^3 of crushed aggregate in ten years which is equivalent to saving about ETB 5.4billion (98million USD) on the crushed stone only. It is evident that we can improve environmental protection by reducing GHGs generated from production equipment and quarrying/disturbing the

natural environment while saving significant amounts of money and reducing the energy required.

The current focus is on expanding the road network. However, it will not be long before the emphasis shifts to preserving the existing road network due to the its rapidly increasing size and the limitations in maintaining and rehabilitating the deteriorating pavements. The current situation, characterised by limited funding, a lack of skill in road network management, and the increasing number of heavy vehicles is contributing to a rapid deterioration of the road network. Thus, it is a critical time to start shifting the emphasis towards preservation of the existing road network. Therefore, the implementation of more timely and proactive preventative maintenance and rehabilitation is needed to preserve the existing roadway infrastructure.

Due to various reasons, including budget scarcity, maintenance interventions in a road system are postponed and pavements are allowed to deteriorate beyond the routine or periodic maintenance level. At the end of their design life, pavements require a rehabilitation intervention, which is a major structural strengthening activity mostly involving removal and disposal of existing damaged asphalt wearing courses. This practice is a non-viable option as it requires the production of virgin natural, crushed stone aggregates, and imported materials such as bitumen, to replace old surfacing. If the current practices are continued the need for virgin materials increases as the number of road segments requiring rehabilitation increase.

The current practice for the rehabilitation of deteriorated asphalt roads is the removal of the existing pavement surfacing and replacing it with a new asphalt mix. The old asphalt removed from the road is usually wasted and dumped by the side of the road. No consideration is given to the environmental impact from both the production of new (virgin) construction materials and the dumping of the removed asphalt surface material. A number of developing countries such as India and South Africa are working on recycling and reusing asphalt pavements, considering the benefits from the environmental impact and the cost savings.

One of the options that looks most promising in improving sustainability, reducing environmental impact and reducing the cost of the rehabilitation of road pavements is the use of old asphalt removed from pavements (Feipeng Xiao et al., 2018) (Kaseer et al., 2019) (Ungureanu et al, 2020) (Magar, et al., 2022) (Bongsuk Park et al., 2020) (Abdalrhman et al.,

2020) (Fujie Zhou et al., 2007) (Wang, et al., 2018) (Giani, et al., 2015) (Ma, et al., 2022) (Zhou, et al., 2017) (Diefenderfer et al., 2020) (Cantrell, et al., 2022) (Wang, et al., 2019) (Amarh et al., 2022) (Moon, et al., 2019) (Barros, et al., 2019) (Diefenderfer et al., 2015) (Veeraragavan, et al., 2017) (Farina et al., 2017) (Hasan, et al., 2020). Asphalt pavement recycling is widely used in the rehabilitation of pavements in the USA and across Europe (ARRA, 2001) where it is regarded as an option for saving costs and reducing environmental impact. Whilst much of the work on Reclaimed Asphalt Pavements (RAP) has been undertaken in developed countries, it has had very limited if any application in developing countries such as Ethiopia. Therefore, the potential application of RAP as in rehabilitating pavements was investigated to identify its benefits and suitability for Ethiopia. Thus, a systematic review approach and an analytical hierarchy process (AHP) was employed to synthesise existing knowledge to determine the weight of evidence confirming its suitability and identify gaps in the knowledge to enable its use in Ethiopia.

However, the attitude that Ethiopia and some other African countries that have highlands in general have plenty of good quality road construction material has precluded the need for recycling of construction materials for road rehabilitation. It is well understood that natural resources are not renewable and their continued unchecked use in large quantities will deplete these resources rapidly. Recycling asphalt used in pavements is a valuable approach for technical, economic and environmental reasons. Its use has been favoured over virgin materials in the light of the increasing cost of asphalt, scarcity of quality aggregates, and the pressuring need to preserve the environment (Al-Qadi, 2007). Therefore, the need to recycle the existing asphalt pavement materials should be explored to create a sustainable pavement system in Ethiopia.

According to the annual survey on the use of recycled materials and warm-mix asphalt by NAPA in the US (NAPA, 2021), the estimated quantity of RAP used in asphalt mixes reached 94.6 million tons in 2021. The economic saving by recycling existing pavement is significant enough that it may allow road agencies to extend the amount of pavement maintenance using the savings made. In the US, the combined saving of asphalt binder and aggregate by using RAP and RAS in asphalt mixes is more than $3.5 billion (NAPA, 2021).

In Ethiopia transportation infrastructure construction is booming and a lot of construction and demolition waste both from the buildings and roads is produced every day. Proper disposal of waste is expensive as it has to be hauled and placed in a suitable landfill. Uncontrolled waste disposal may result in significant environmental impact. In Ethiopia, there are some small efforts to recycle or reuse some of the waste in roads and it can both save money and result in societal benefit. As an example, over 15 years ago in the rehabilitation of the A1 trunk road Addis-Modjo, the existing asphalt pavement was milled and the material was reused as a base course on the same road. At the time, the cost savings as a result of the minimised virgin aggregate and the general benefits anticipated by using new technology in the road sector was highly regarded by the professionals in the road sector. Though this effort was appreciated by professionals, it did not continue and was not supported by a policy or a strategic plan for recycling of pavement materials.

In this research, current recycling technologies, both cold and hot methods, will be evaluated based on selected criteria for their suitability for local conditions. In addition to this, the current approach to design asphalt pavement rehabilitation in Ethiopia will be assessed with respect to using recycled asphalt. This study will also focus on recycling methods with consideration of cost savings, environmental impact, energy consumption and performance. Based on the outcome, the appropriate asphalt pavement recycling method that helps to sustain the road infrastructure in Ethiopia will be developed or selected along with a policy framework.

1.2 Problem statement

High quality pavement construction materials are limited and expensive, escalating road construction costs. Materials such as natural or crushed aggregates for road making are non-renewable and continued use will deplete this resource, compromising the supply for the future generations. The production and transportation of new materials for pavement construction necessitate the use of heavy machinery that can produce greenhouse gases, which are harmful to the environment and require more energy. This ultimately makes our pavement system non-sustainable and environmentally unfriendly.

The cost of bitumen is periodically increasing, along with the cost of production and transportation of good quality aggregates; while continued use of the natural resources leads to

their depletion, affecting the environment. Therefore, there will be a need to optimise the use of natural resources, reduce energy consumption, and reduce greenhouse emissions by limiting pollution. Ultimately, this will increase sustainability in road construction and maintenance.

A significant amount of the country's budget goes into the construction of roads and the asphalt network is increasing. This means a lot of maintenance will be needed and a heavy rehabilitation burden to carry in the coming few years to keep the road network in a serviceable condition. The need for rehabilitation and maintenance increases, which means a significant amount of scarifying and wasting of the existing asphalt pavement sections. Therefore, it is very important to recycle existing deteriorated pavements than scarify and waste this material.

1.3 Rationale of the research

Rehabilitation and reconstruction of existing asphalt pavements needs to be carried out in an environmentally friendly manner, with the minimum cost and in a shorter time with less disruption to the traffic movement or flow. This can be achieved through recycling the existing pavement materials and using them on the same roadway. Thus, it is important to better understand the recycling methods currently available, their advantages and disadvantages, their application, and their properties. This research is then important in creating awareness about asphalt pavement recycling and paves the way for its wider use in the coming years to benefit from the advantages obtained by appropriately using the recycling technology in Ethiopia.

There are four clear novelty aspects of this study:

i. Recycling type selection method was developed through the use of established selection criteria and questionnaire analysis which is unique in its nature to Ethiopia.
ii. Laboratory investigation of potential performance of mixes containing RAP materials from a failed road section in Ethiopia. The mix proportions included up to 90% RAP material. This work is novel as RAP has not been used in Ethiopia before.
iii. Life Cycle Cost analysis of using RAP materials in Ethiopia was carried out using HDM-4 software. This indicated potential savings that can be obtained by using RAP materials that is unique to Ethiopia.
iv. One of the hinderance factor for not implementing asphalt pavement recycling in many developing countries is lack of proper guidance and supports to encourage the

road maintenance contractors or road agencies. The development of policy framework that is unique to Ethiopia based on questionnaires analysis is novel and may be adopted by other similar countries.

1.4 Aim of the study

The aim of this research is to develop a procedure for selecting the most cost effective, environmentally friendly and energy saving method of asphalt pavement recycling that can be used in both new construction and rehabilitating existing roads in Ethiopia.

1.5 Objectives of the study

Specific objectives of this project are as shown below.

i. Understand the applications, advantages and limitations of the various pavement recycling methods.

ii. Undertake a systematic evaluation of information published.

iii. Select the best performing asphalt pavement recycling method that can be implemented in Ethiopia for rehabilitation and reconstruction of asphalt roads.

iv. Develop evidence-based guidelines for the use of asphalt pavement recycling technology in Ethiopia.

v. Explore the development of a policy framework to guide and support the use of Reclaimed Asphalt Pavement materials in road maintenance and rehabilitation.

1.6 Scope of the study

This study focuses only on flexible asphalt pavements with Asphalt Concrete (AC) surfacing. Recycling of Rigid pavements are not considered and also the recycling of thin bituminous surfacing including double bituminous surface treatments (DBST) and triple surface treatments (TST) are not included. However, the use of Reclaimed Asphalt Pavement materials in thin bituminous surfacing is considered in this study. The study will look into all currently available

asphalt pavement technologies, laboratory experiments for performance evaluation and economic analyses of Reclaimed Asphalt Pavement materials.

Based on the result of literature review and identified gaps in the information for developing countries, laboratory investigation and life cycle cost analysis was included in this research to address the gap identified during the literature review.

1.7 Definition and conceptual issues

Asphalt pavement recycling technology is widely used in the rehabilitation of pavements and is regarded as an option for cost saving and reducing environmental impact (Kandhal, 1997) (Jitareekul, 2009) (Chen, 2007). A number of techniques are available for reusing asphalt in new-build or in effecting repairs/rehabilitating old roads. One of the challenges is how to select the most cost-effective method suitable for the local conditions in terms of the whole-life cost. Once a suitable recycling method for the Ethiopian conditions is identified and implemented, it is believed that the following benefits will be obtained for the road sector:

- Reduced cost of construction and maintenance due to reuse of existing asphalt materials;
- Reduced amount of energy needed as a result of less production and transportation of virgin materials;
- Reduced waste from road rehabilitation and reconstruction process.

In order to help better organise the research and focus, concepts related to asphalt pavement recycling and recycled materials are as defined below.

- **Asphalt Pavement Recycling:** refers to re-processing of an existing pavement by milling and mixing appropriate stabilisers as needed for the purpose of reusing it in the rehabilitation/reconstruction of pavements.
- **Cold Planning:** the controlled removal of an existing pavement to a desired depth, longitudinal profile, and cross-slope, using specially designed equipment (AARA, 2001).
- **Cold In-place Recycling (CIR):** a process that uses cold milling of the surface and remixing with the addition of asphalt emulsion, Portland cement, foamed asphalt, or other additives to improve the properties of the reclaimed asphalt pavement (RAP), followed by placing and compacting the new mix in one continuous operation (NCHRP 421, 2011).

- **Hot In-place Recycling (HIR):** a process that preheats the existing surface immediately before milling, mixing the RAP with asphalt binders, recycling agents, new aggregates, or other additives to improve the properties of the RAP, then placing and compacting the new mix in one continuous operation (NCHRP 421, 2011).
- **Full Depth Reclamation (FDR):** FDR is the rehabilitation technique in which the full thickness of the asphalt pavement and a predetermined portion of the underlying materials (base, sub-base and/or sub-grade) is uniformly pulverised and blended to provide an upgraded, homogenous base material.
- **Reclaimed Asphalt Pavement (RAP) Materials:** is the term given to removed and/or reprocessed pavement materials containing asphalt and aggregates. These materials are generated when asphalt pavement layers are removed for reconstruction, resurfacing, or to obtain access to buried utilities. When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt cement (FHWA-RD-97-148, 2008).

1.8 Structure of the thesis

This thesis is divided and presented in eight chapters. The first chapter deals with the introduction to the study. In this chapter the background of the study, the problem statement, the aims and objectives including the methodology followed are presented.

Chapter Two presents the methodology followed in this study. In this chapter it is shown how asphalt pavement recycling economic and physical performances are assessed, development of recycling methods selection, and establish the necessary policy framework required for the smooth implementation of asphalt pavement recycling.

Chapter Three is about the literature review of asphalt pavement recycling. The main focus area are types of recycling, Reclaimed Asphalt Pavement (RAP) materials and their production and handling, and benefits of asphalt pavement recycling are discussed in details. A systematic literature Review approach is employed to search and select relevant literature, and then conduct in-depth review of selected literature was conducted.

Chapter Four is dealing with the development of the pavement recycling selection method to be used in the process of pavement rehabilitation involving recycling of the existing pavement. The

development of selection criteria and evaluating their importance is presented. The method used to evaluate the importance of the developed selection criteria is described, and based on the selection criteria, the asphalt pavement recycling methods are evaluated and presented in this chapter.

Chapter Five presents the results and analysis in which the result of the pavement recycling methods' selection and a systematic review are analysed and discussed in detail.

Chapter Six discusses the development of policy framework through questionnaire survey and analysis combined with results of literature review.

Chapter Seven presents the discussions on the test conducted and their results and Chapter Eight presents the conclusion and recommendations of the study.

2 METHODOLOGY

2.1 Introduction

The research methodology described in this chapter includes methodology adopted for a literature review, questionnaire survey and interviews, policy framework, laboratory testing and a life-cycle analysis. A systematic literature review method was used to analyse the information in the literature. The literature review findings in terms of recycling asphalt were used to assess their suitability for Ethiopia using a questionnaire survey. The literature review was also used to design and assess the performance of RAP materials with a laboratory-based investigation. The laboratory study used samples collected from a failed section of existing pavements in Ethiopia. The economic benefits part of the study in terms of the life-cycle analysis was conducted using HDM4, a computer software for Highway Development and Maintenance Management System. It is a decision-making tool used to check engineering and economic viability of investment in road projects. The outline of the overall methodology adopted in this study is shown in the flow chart shown in Figure 2.1.

2.2 Systematic Literature Review

A thorough and detailed literature review was conducted using a systematic review technique (Burrow, 2016). This can be summarised as follows:

i. Identify the research question
ii. Develop a list of key words related to the question; 17 key words were developed for this study
iii. Identify suitable search engines
iv. Search the literature using all the key words for each search engine in turn; 45000 articles were found
v. Develop inclusion criteria to filter all the literature; only 70 articles were considered suitable
vi. This list was reduced to 48 after applying a filter based on types of recycling; information in these 48 publications was analysed in detail.

The above approach is summarised in a flow chart shown in Figure 2-1. and is described in detail in the following section.

The key questions for the literature review survey were:

1. What types of asphalt pavement recycling technologies are available?
2. What are the benefits of recycling asphalt pavements in the context of developing countries?
3. How do you characterise recycled materials?
4. How do recycled pavements' materials perform in a hot climate (in tropical countries)?

It is necessary to answer the research questions in the given sequence as answers from the preceding questions inform the following question. Thus, in developing a method for selecting the type of recycling for the asphalt, it was necessary to ascertain the types of relevant technologies available and their benefits.

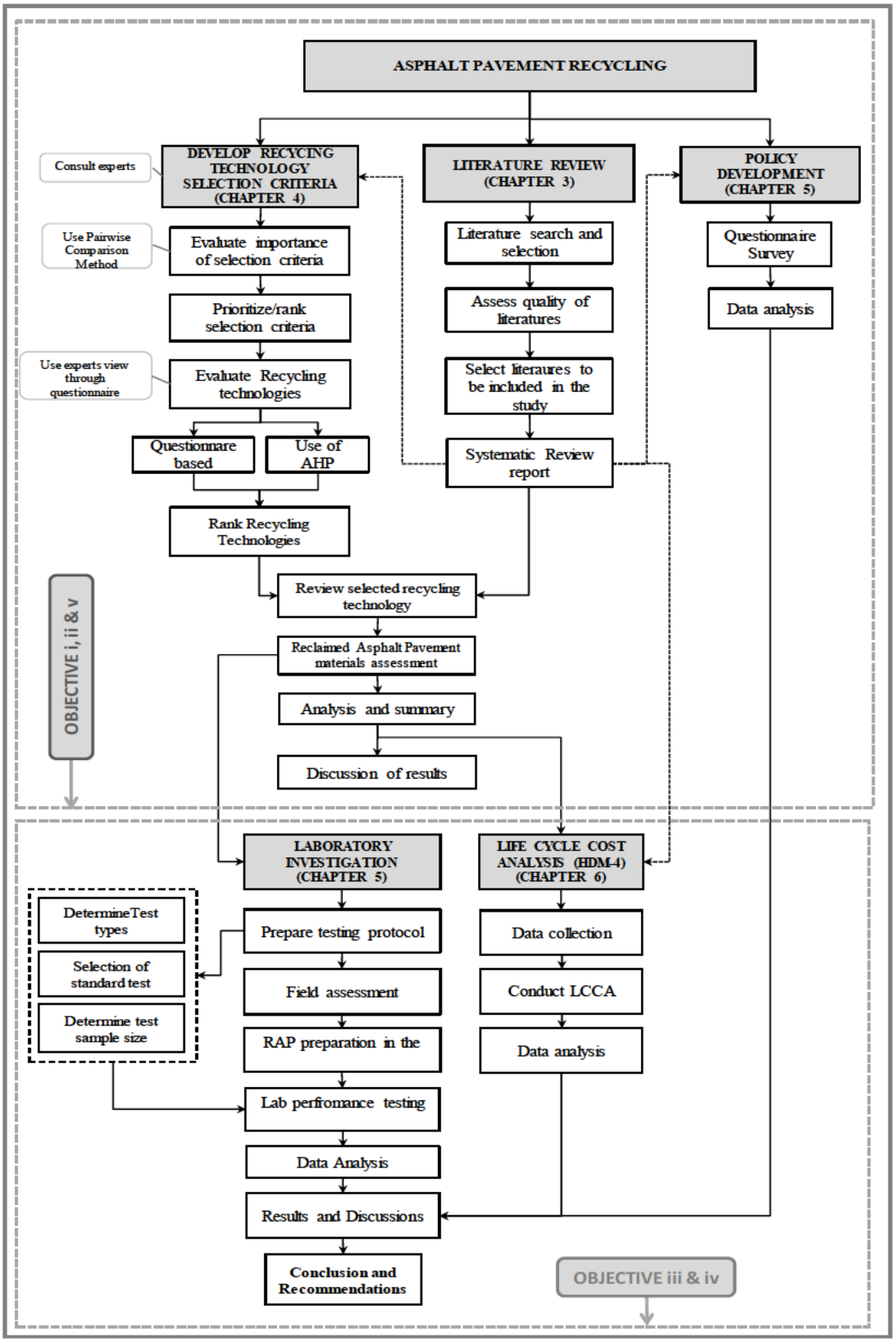


Figure 2-1Methodology flowchart

2.2.1 Selection of relevant studies

Seventeen key words and phrases relating to research questions were used to undertake literature searches. Three search engines were identified as being the most relevant (Google Scholar, Science Direct and Research Gate). However, the International Journal of Pavement Engineering, the International Journal of Construction Education and Research, the Institute of Civil Engineers, the Journal of Road Materials and Pavement Design, NCHRP and FHWA, the Conference on Asphalt Pavement of South Africa and the University of Birmingham Library websites were also used in the systematic search. An exhaustive search for publications was then undertaken using all the key words for each search engine and websites (noted above) in turn, until no new references could be found. This yielded 45,000 articles. At this stage, the selection was made only based on the titles. At the end this stage, abstracts of each paper were examined to assess the type of the study, the extent of the coverage of the topic, and the lists of references were also examined, further reducing the number of potentially suitable documents to 34,000. All the references were then examined in detail in terms of the final inclusion criteria based on detailed coverage of the topic listed and the robustness of information in terms of coverage of different types of recycling and their application. At the end of this stage, the number of papers was reduced to 70; these included 48 papers that covered cold recycling, hot recycling and full depth reclamation. Though relevant, the remaining 22 articles were review papers that were not considered to be the primary source of information, but they provided good coverage of the topics.

Although the asphalt pavement recycling dated back to 1915, it was apparent that RAP was a relatively recent phenomenon as only 10% of all the publications were dated between 1915 and 2000. This review was limited to post 2000 publications, covering about 90% of all the literature, with about 50% of all the publications being post 2010. The number of publications by year are shown in chapter three, Figure 3.3.

Significant publications comprised articles in journals, reports and conference papers respectively in proportions of 52%, 16.4%, and 12.2%. Therefore, it can be seen the studies included are mostly journals, reports and conference papers. Most of the studies were limited to developed countries such as the USA (40%), Australia (6%) and the UK (5.6%), as no significant studies were available from African countries or other underdeveloped countries, though some

information was available from Nigeria, India and Brazil. Distribution of the publications on a country basis is shown in chapter three, Figure 3-4.

2.1.1.1 Selection Criteria

Five criteria used to assess the weight of evidence at the final stage of filtering of papers are shown in Table 2.1, which also gives the weighting attached to each element of each criterion, where values applied to each descriptor were allocated based on their importance.

Table 2-1Weight of evidence in the literatures

		Weighting	
	Quality Assessment Checklist	**Descriptor**	**Value**
A	**Is asphalt pavement recycling sufficiently described in the study?**		
	Sufficient detail for the recycling types is provided	High	1
	Relatively sufficient or satisfactorily detail of the recycling types provided	Medium	0.67
	Description of the recycling is too general or vague	Low	0.33
B	**Benefits of asphalt pavement recycling methods included?**		
	Benefit or advantage of the recycling technology is presented in sufficient detail	High	1
	Benefit or advantage of the recycling technology is presented satisfactorily	Medium	0.67
	Benefit or advantage of the recycling technology is presented with no sufficient detail and not supported by evidence of durability or economic advantage	Low	0.33
C	**Does the study include RAP material characterisation?**		
	Characterisation of RAP material, laboratory investigation methods and standards used are given.	High	1
	Laboratory investigation is included but no indication of standards employed	Medium	0.67
	Characterisation is vague or too general, or only results are given	Low	0.33
D	**Relevance of the studies**		
	Focuses on recycling technologies applied to asphalt pavements with material obtained from the road. This may include use in DBST, etc.	High	1
	Include other bituminous materials (e.g., recycled asphalt shingles - RAS)	Medium	0.67
	Includes only non-asphalt recycled materials used in pavements (concrete road, gravel roads, etc.)	Low	0.33
E	**Performance data included in the study**		
	Field and laboratory performance data is available in sufficient quantity and detail. Field performance includes minimum 5 years continuous assessment data.	High	1
	Either field or laboratory performance data is not available or if the performance is presented qualitatively.	Medium	0.67
	Either field, laboratory performance data or qualitative information is not available.	Low	0.33

2.2.2 Synthesis of Evidence of Suitability of Recycling

The information regarding the suitability of asphalt pavement recycling was synthesised based on the suitability criteria listed below.

i. Cost effectiveness
ii. Environmental sustainability
iii. Ease of construction
iv. Energy saving
v. Economic sustainability
vi. Minimised use of virgin materials
vii. Suitable for low volume sealed roads
viii. Suitable for labour intensive work
ix. Suitable for different climatic conditions
x. Suitability for small scale contractor

These criteria were developed based on the literature review and interviews and discussions with professionals at the Ethiopian Roads Administration so that the criteria will reflect the local conditions such as economic and technological status of Ethiopia.

2.2.3 Evaluation of Selection Criteria using Analytic Hierarchy Process (AHP)

The criteria listed in section 2.2.2 do not have equal weighting, as some of them have greater importance compared to others. Therefore, a multiple criteria analysis based on a pair-wise comparison method was used to analyse the importance of each criterion. Pair-wise ranking is a method of prioritising or ranking identified lists of problems or objectives. The analysis was undertaken using the following steps as proposed by Saaty, 1990.

Step 1: Define the Goal: the goal of this exercise was to "evaluate and select the appropriate recycling method" that is suitable for Ethiopia.

Step 2: Define the criteria: suitability criteria were developed, defined and evaluated in this process of the pair-wise comparison method.

Step 3: Select the alternatives: alternatives were identified based on asphalt pavement recycling methods currently available.

Step 4: Structure the hierarchy: prepare the hierarchy based on the goal, criteria and alternatives, see Figure 4-1.

A matrix of the alternatives to be compared was prepared and values of judgments (referred to as vector judgement values) were assigned based on the experience of experts who were asked to fill the matrix. Each expert evaluated the importance of one criterion over another based on the scale given in Table 4.1. Then the average value was taken to derive a single reciprocal matrix as defined by Saaty, 1990.

2.2.4 Questionnaires and interviews

In the preceding sections the systematic review approach adopted for extracting and synthesising global information regarding the recycling methods is described. Almost all the information relates to developed countries. So, a questionnaire was developed to evaluate asphalt pavement recycling methods that can be implemented in developing countries. It was sent to local and international experts in the area of pavement and materials' engineering who understood the asphalt pavement recycling technologies. The questionnaire was aimed at evaluating the recycling types by criteria developed used in the systematic review. The results of the questionnaire were analysed in conjunction with the importance factors of the criteria obtained using the AHP method.

2.2.5 Policy Framework

Innovative processes and product models shall be established towards achieving goals of policy-focused sustainable development (Mantalovas, et al., 2019). Asphalt pavement recycling or other innovative approaches in the process and product development are believed to have a lack of policy framework and provision of suitable guidance; this is considered to be a significant hinderance in using RAP in developing countries. The literature is also not clear which type of recycling method to select, why and where to apply it.

Therefore, in order to develop the use of RAP in Ethiopia, it was decided to develop a policy framework and strategy for the implementation of asphalt pavement recycling. This was done through interviews and questionnaires to assess the current situation and literature reviews, specifically the experiences of those who have a policy framework on asphalt pavement recycling. The FHWA has issued a recycled materials' policy that promotes the benefits of

recycling, gives priority to recycled materials, and discourages restrictions on recycled materials without technical justifications. Such policy statements give strength to recycling efforts especially at the beginning stage. Accordingly, a questionnaire was developed and distributed to local experts and leaders in the industry to assess the impact of the policy on the implementation of asphalt pavement recycling.

2.3 Laboratory test

Whilst there are a number of publications that give properties and mixed designs using RAP, most of that data is related to developed countries and there is none that relates to sub-Saharan Africa. It was therefore essential to undertake a laboratory study to determine the properties of RAP in order to estimate its longer-term behaviour. A laboratory investigation of Reclaimed Asphalt Pavement materials was undertaken at the Ethiopian Road Administration's Road Research Centre laboratory in Addis Ababa. The RAP materials' sample was collected from the Bedele - Metu Road segment located in the western part of Ethiopia. Samples were collected in a block shape and carefully prepared in the Road Research Centre (RRC) laboratory for different tests according to the need for a specific test type and were prepared and tested in accordance with the test procedure outlined under section 2.3.2.

2.3.1 Preparation of RAP containing mixes

Test specimens were prepared at the RRC laboratory for testing and determination of performance characteristics of different RAP percentages in the mix and then compared with the characteristics of the control mix. Asphalt containing 20%, 30%, 40%, 50%, 70%, and 90% RAP are were investigated. The main performance tests required in this research were: the Marshall stability test, the indirect tensile strength (ITS) test, the resilient modulus, and the rut resistance tests.

The Marshall mix design for the HMA mixes containing RAP at different proportions was carried out. The job mix was determined and the mixes were prepared accordingly. Table 2-2. shows the blending of virgin and RAP material proportioning.

The bitumen content was determined based on extraction the test result and the optimum bitumen content for the control mix, which is 5%. Accordingly, the amount of bitumen to be added in the

RAP containing mixes was determined based on the amount of RAP used for blending with virgin bitumen and aggregates.

Table 2-2 Job mix for sample preparation

	% of Aggregate in the mix			Weight of aggregate in the mix							
% RAP	Coarse	Intermediate	Fine	Coarse	Intermediate	Fine	WT of RAP in the mix	Wt. of Virgin	Wt. of RAP and Virgin bitumen	Wt. of Virgin aggregate in	Total Wt. of material in the mix
0	64.0	15.1	15.9	768.4	181.3	190.4	0.0	60.0	60.0	1140.0	1200.0
20	57.9	13.7	14.4	695.1	164.0	172.2	120.0	48.74	168.7	1031.3	1200.0
30	51.5	12.1	12.8	618.0	145.8	153.1	240.0	43.08	283.1	916.9	1200.0
40	45.1	10.6	11.2	540.9	127.6	134.0	360.0	37.44	397.4	802.6	1200.0
50	31.9	7.5	7.9	382.9	90.3	94.9	600.0	31.86	631.9	568.1	1200.0
70	19.1	4.5	4.7	228.8	54.0	56.7	840.0	20.60	860.6	339.4	1200.0
90	6.2	1.5	1.5	74.6	17.6	18.5	1080.0	9.36	1089.3	110.7	1200.0

It was essential to undertake a laboratory study to determine the properties of RAP from a road in Ethiopia which had been subjected to local environmental and traffic conditions in order to estimate its long-term behaviour and was tested in accordance with the test procedure outlined below.

2.3.2 Laboratory Test Procedure

The various stages of sample collection and preparation and laboratory testing program are described below and are given in Fig. 2.2 in the form of a flow chart. Sample preparation and test program is shown as follows.

1. RAP sample material was collected from an existing pavement, taken to the laboratory and cleaned to remove any contaminants and debris.
2. New bitumen and virgin aggregates were used for making the control mix.
3. Test specimens were prepared in the laboratory to conduct a characterization test. Accordingly, bitumen extraction was carried out to determine the bitumen content and PSD in the mix.
4. Benzine was used for the extraction of bitumen at the ERA Road Research Centre and trichloroethene was used at the Chinese Laboratory in Addis Ababa

5. The extraction test was conducted on asphalt from old pavement after being heated in an oven for one hour to make the RAP material loose enough for pouring and to remove any residual moisture.
6. Centrifuge extractor (AASHTO T164A) was used for the extraction process
7. After extraction, Particle Size Distribution, PSD, of recovered aggregate was carried out.
8. The separated bitumen was recovered by evaporation of the solvent following the solvent recovery method (AASHTO T164A) at the Chinese Laboratory to determine the penetration of the recovered bitumen.
9. A control mix was prepared using virgin aggregate and bitumen.
10. Asphalt samples containing 20%, 30%, 40%, 50%, 70%, and 90% of RAP were prepared for the following tests.
    a. Indirect tensile strength,
    b. Resilient modulus test
    c. Permanent deformation and
    d. Marshall stability

    It was planned to conduct the test starting from 10% RAP in HMA, however, at later stage it was decided to drop the 10% as a lot of work has already been done on this and sufficient information is available.

11. Data from the test was analyzed to determine the optimum percentage of RAP at which the highest performance is obtained.

Detailed laboratory tests plan is shown in Figure 2-2.

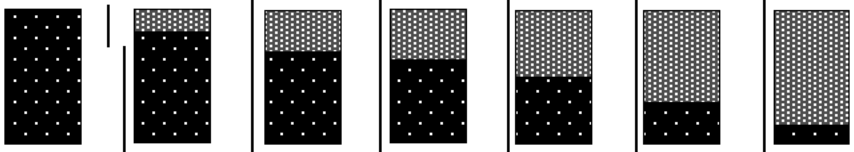
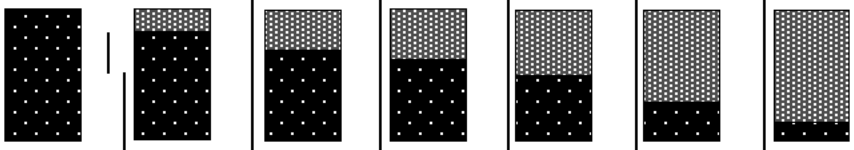
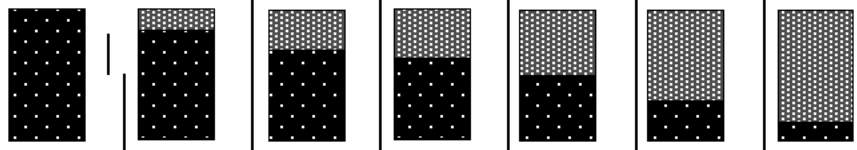
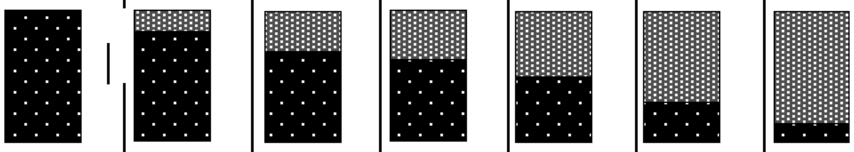
No.	Test types % combination	Proportions of RAP with Virgin materials (Vmat)						
1	Resilient Modulus No of Samples for each combination = 2 (2 x 7 = 14 samples)							
		Control Mix (VMat)	20% RAP +80% VMat	30% RAP +70% VMat	40% RAP +60% VMat	50% RAP +50% VMat	70% RAP +30% VMat	90% RAP +10% VMat
2	ITS (indirect Tensile Strength) No of Samples for each combination = 2 (2 x 7 = 14 samples)							
		Control Mix (VMat)	20% RAP +80% VMat	30% RAP +70% VMat	40% RAP +60% VMat	50% RAP +50% VMat	70% RAP +30% VMat	90% RAP +10% VMat
2	Permanent Deformation (Rutting) No of Samples for each combination = 2 (2 x 7 = 14 samples)							
		Control Mix (VMat)	20% RAP +80% VMat	30% RAP +70% VMat	40% RAP +60% VMat	50% RAP +50% VMat	70% RAP +30% VMat	90% RAP +10% VMat
2	Marshall Stability No of Samples for each combination = 2 (2 x 7 = 14 samples)							
		Control Mix (VMat)	20% RAP +80% VMat	30% RAP +70% VMat	40% RAP +60% VMat	50% RAP +50% VMat	70% RAP +30% VMat	90% RAP +10% VMat
	Total No of samples	8	8	8	8	8	8	8
		56 samples						

Figure 2-2 Laboratory test plan

Notes about the test program:

1. Gradation of crushed stone was determined in accordance with the ERA 2014 design guide for surfacing (Ethiopian Roads Authority, 2013)
2. Bitumen type used was 60/70 penetration grade
3. The quantity of bitumen added was based on the extraction from the RAP materials
4. RAP = recycled Asphalt Pavement
5. Vmat = virgin Material
6. Two Test samples were tested due to sample size limitation and time constraint at the RRC laboratory.
7. Mix preparation
    i. RAP Material
        - RAP Material was hand crushed taking care not to crush crushed stones (in the RAP)
        - Heat the RAP material in oven before mixing with virgin materials at 120 - 140ºC for one day

    ii. Vmat: Virgin material mix was prepared based on the specification of ERA 2014 Design guide

    iii. The RAP and Vmat mixes were then mixed together in the assigned proportion to produce test samples for each type

2.2.2.1 Marshal test

The Marshall test was mainly conducted to assess the stability and flow of the asphalt mixtures using the ASTM D6927 test method. The control mix was prepared with virgin materials to assess the effect of the RAP material for a performance evaluation. The Marshall method of the mix design was followed, based on the data from ERA. All the required tests were carried out on the control mix and later were used for the purpose of comparing against the performance of the RAP containing the mixes.

2.2.2.2 Rutting

Asphalt pavement rutting occurs as a longitudinal depression along the wheel path due to traffic loading. Rutting or permanent deformations in pavement layers may be in the underlying layers; however, in this research, deformation in the asphalt layer only was considered as the aim of this

study was to determine the rutting potential of asphalt containing RAP in different proportions. One of main problems regarding the performance of asphalt pavements is the potential for rutting, especially where there is a considerable proportion of heavy goods vehicles in areas of high temperatures. Accordingly, it was important to have a design that can resist the formation of rutting. The literature indicates that pavement layers stabilised with RAP materials perform equally or better compared to non-stabilised or virgin materials (Ungureanu et al, 2020). So, whilst the literature indicated types of mixes that can be suitable, it was deemed important to develop mixes based on materials available in Ethiopia.

Table 2-3 Wheel tracking test preparation

Specimen preparation	
Mass of sample used for the experiment	11,000 g
Bitumen content	5%
Specific gravity of binder	1.03
Aggregate heating temperature	165 ºC
Virgin bitumen heating temperature	150 ºC
RAP heating temperature	130 ºC
Mixing temperature (RAP & virgin material)	150 ºC
Specimen used for each test	Two for wheel tracking
Compacting slab specimens' thickness	305 mm x 305 mm x 50 mm
Specimens' compaction	Linear kneading compactor
Compaction load	800 N
Compaction temperature	145 ºC
Number of passes	21
Compacted specimens and the mould cooling	Room temperature for 24 hrs
Then samples and the mould heated in oven	16 hrs at a temperature of 60 ºC
Heat the wheel tracking machine to (and at this temperature the samples in the mould were mounted rigidly to the tracking machine)	60 ºC
Wheel Tracking Testing/Rutting	
Roller type	Pi 203x50 rubber
Load applied	705± 4.5 N
Pretesting/cycle	25
Testing wheel cycles/pass	20,000
Sample testing temperature	60 ºC
Roller/wheel speed	53

Thus, in the evaluation of the performance of asphalt pavement recycling methods rutting was considered to be an important criterion. Accordingly, the laboratory test programme was designed to evaluate the rutting resistance for different proportions of RAP in the asphalt mix.

The wheel tracking device at the Road Research Centre was used to check the rut depth at 20,000 cycles for all proportions of RAP in the mix. The AASHTO T324-04 test method for rut measurement was followed. Table 2-3. summarises information about the test and preparation of samples.

2.2.2.3 Indirect Tensile Strength (ITS)

Some literature refers to this test method as the "IDT Test", however for this research the term indirect tensile strength (ITS) test is used, as it is used by ASTM D 6931 and Eurocode (EN 12697-23). The main purpose of this test is to determine the rutting potential or cracking of the mix. In this research the primary objective of this test is to evaluate the cracking potential of the mixes containing RAP materials. Rutting potential is determined separately by using the wheel tracking test method. This test was conducted according to the ASTM 6931. The procedure followed for the ITS is shown in Table 2-4.

Table 2-4 Indirect Tensile Strength test preparation

Weight of aggregate used for the mix	1200 g
Bitumen content	5%
Specific gravity of bitumen	1.03
Specimen size	Height (average =64.3 mm), Diameter (average 101.4 mm)
Aggregate heating temperature	165 ºC
Virgin bitumen heating temperature	150 ºC
RAP heating temperature	130 ºC
Mixing temperature (RAP and virgin materials)	150 ºC
No. of specimens used for each test	Two
Compaction temperature	145 ºC
Marshall compaction	75 blows each side
Cool at room temperature	for 24hrs
Placed the specimen in thermostatically controlled water bath for one hour at a temperature of 25 ºC	
Vertical applied load	Until maximum load is reached
Deformation rate	50 mm/min

2.2.2.4 Resilient modulus (M_R)

This is defined as the ratio of the applied stress and recoverable strain at a particular temperature and load in a cyclic loading test used to evaluate stiffness of a material. The resilient modulus value is a point where the ratio between the deviator stress and the recoverable strain is constant for that material. It is determined from the results of this method and used to evaluate the stiffness of the mixes.

2.4 Life cycle cost analysis using HDM-4

The economic performance using an asphalt mix containing RAP materials was evaluated with the HDM4 economic model to determine the optimum mix proportion that will give the best economic advantage. HDM4 was selected for this purpose because:

i. It is a well-established and robust method when it comes to both engineering economic evaluations for road projects; and
ii. The system is developed based on large scale field experiment world wide
iii. It was developed and used by international organizations like the World Bank and has a good track record.
iv. Compared to other LCCA systems such as from FHWA, it is more robust and have the options to be used as a default value for those items where you may not get the necessary input data.

It is well understood that HDM4 need to be calibrated to local conditions and requires a lot of data to come up with sound and reliable output. In this research the calibration factors developed by (Berhanu, 2022) for Ethiopia, shown in Table 2-5, were used.

Table 2-5 HDM-4 calibration factors (Abeba Birhanu, 2022)

Pavement type	Traffic level	Crack initiation K_{ci}	Crack progression K_{cp}	Rut depth progression K_{rp}	Roughness age environmental coefficient (K_{gm} /K_{ge})	Roughness progression factor K_{gp}
AC*	High	1.1	0.91	1.00	0.87	1.00

AC* means Asphalt Concrete

The analysis was carried out for all the RAP mix proportions of asphalt mix and the control mix to investigate the economic benefits that can be obtained (using RAP). The economic benefit was evaluated in terms of the life-cycle cost of each mix's proportion. All input data and calibration parameters were relevant to the location from where the test samples were collected, so as to reflect the real scenario of the pavement performance and economic situation and to obtain realistic results of the analysis. The economic analysis was based on the net present value to evaluate and compare the benefit of each mix containing the RAP material. Rutting and roughness (IRI) were used to evaluate the performance of pavement constructed using RAP containing HMA mixes.

3 LITERATURE REVIEW

3.1 Introduction

With the increase of the road network size and the need to keep the pavements in a serviceable condition all the time, maintenance and rehabilitation becomes more and more important, requiring the highest attention from the government and road agencies. Especially in the areas where there is shortage of virgin aggregates, the issue of maintenance and rehabilitation becomes critical. The continuous withdrawal of virgin materials for road construction and maintenance has a negative environmental impact and depletes the natural resources. Recycling or reusing the existing pavement material in the process of the rehabilitation of roads provides a significant contribution towards addressing the problems of the shortage of good quality materials, and minimising the adverse environmental impact.

In Ethiopia, more emphasis is given to the construction of new roads and less attention to maintenance of the existing road pavements; note that maintenance activity is also carried out using the conventional method employed for new construction. The traditional method may be suitable for rehabilitation and maintenance; however, it is a very slow process, particularly when working under traffic. Additionally, it is relatively inefficient as it is difficult to make use of the *in-situ* material from the existing pavement (Lewis, 1999). The need for good construction materials is increasing and an alternative means for the maintenance and rehabilitation of road pavements is becoming critical. Recycling and reusing of materials from the existing pavements are now becoming more attractive concepts and are considered better alternatives from many perspectives.

Recycling or reuse of pavement material is a very simple but powerful concept and its inception dates back to 1915 (Kandhal, 1997). Recycling of pavements is a technique whereby an existing degraded pavement is modified and transformed into a homogeneous structure that can support the traffic requirements. Asphalt recycling is not a new concept and has been practiced for many years in the past. The Romans are thought to have been the first to develop recycling technology more than 1900 years ago (Richardson, 1994). The first documented case of asphalt recycling, in the form of hot in-place recycling (HIR), was also reported in the literature of the 1930s (ARRA, 2001). More advancement of this technology was not realised until the 1970s because of limited

resources and knowledge. Only moderate advancements in asphalt recycling technology and equipment occurred until the mid-1970s (ARRA, 2001).

According to (ARRA, 2001), due to two major events since the 1970s asphalt pavement recycling revived. The first event was the petroleum crisis and the development and introduction in 1975 of large-scale cold planning equipment. Since that time, the equipment manufacturing and construction industries have been proactive in the development of asphalt recycling methods and technologies which have advanced exponentially in the last 25 years (ARRA, 2001). Another event which gave a boost to the asphalt pavement recycling was in the early 2000 where the cost of oil significantly increased and so did the shortage of good quality aggregate (Esenwa, 2013).

Asphalt pavement recycling has continually increased in the recent years and a lot of research is being conducted in many countries to maximise the benefit of recycling. The interest in using RAP materials has increased mainly due to its cost saving and increased environmental awareness (Al-Qadi, et al, 2011).

According to the 6th annual survey on the use of recycled materials and warm-mix asphalt by NAPA (Hanson, 2015), the estimated tons of RAP used in asphalt mixes in the USA reached 74.2 million tons in 2015. The economic saving by recycling existing pavements is significant and may allow road agencies to extend the amount of pavement maintenance expenditure. The combined savings of asphalt binder and aggregate by using RAP and RAS in asphalt mixes is more than $2.8 billion. This keeps asphalt pavement mixture costs competitive and allows owners to achieve more roadway maintenance and construction activities within limited budgets (Hanson, 2015).

Recycling of asphalt pavements is a valuable approach for technical, economical, and environmental reasons and the use of recycled asphalt pavements has been favoured over virgin materials in light of the increasing cost of asphalt, the scarcity of quality aggregates, and the pressuring need to preserve the environment (Kennedy, Tam and Solaimanian, 1998). Therefore, recycling of the existing asphalt pavement materials should be explored to create a sustainable pavement system.

A systematic review technique was adopted in this thesis to ensure that the findings were robust, evidence based, transparent and reproducible (Tranfield et al., 2003). The specific research questions addressed in this study were:

1. What types of asphalt pavement recycling technologies are available?
2. What are the benefits of recycling asphalt pavements?
3. How can we select recycling types?

3.2 Types and overview of asphalt pavement recycling

The following techniques of asphalt pavement recycling are available for analysis and they are described as follows.

3.2.1 Cold planing

Cold planing is the controlled removal of an existing pavement to a desired depth, longitudinal profile, and cross-slope, using specially designed equipment. Asphalt pavement millings are obtained from the planing work and the milled material is typically consistent in its lump size distribution. The material removed from the pavement is granular asphalt bound material and is removed from the site and sent to stockpile or in some cases to a landfill, especially where there is no experience of recycling. However, this reclaimed material is a very important material that can be reused in the applications of pavement rehabilitation and reconstruction.

It is useful for the removal of wheel ruts, a deteriorated pavement surface or oxidized asphalt. It is also used in the correction of the longitudinal profile, and the preparation of the surface for other pavement recycling works.

3.2.2 Cold in-place recycling

Cold in-place recycling (CIR) is a process that uses cold milling of the surface and remixing with the addition of asphalt emulsion, Portland cement, foamed asphalt, or other additives to improve the properties of the reclaimed asphalt pavement (RAP), followed by placing and compacting the new mix in one continuous operation (NCHRP, 2011).

In the past there was a practice to classify cold in-place recycling or full depth recycling (FDR). However, the definitions have now become clearer (Cox, 2013); CIR is recycling of the majority

of the existing asphalt concrete layer, whereas, FDR refers to the recycling of all existing asphalt concrete layers and a significant portion of the underlying layers.

Cold in-place recycling (CIR) involves reuse of the existing pavement material without the application of heat (Kandhal, 1997; Chen & Jharen, 2007; Lee, 2014). As only a certain defined percentage of virgin material is added, the associated cost of transportation is minimised in the rehabilitation operation. According to the study by (Kazmierowski, 1992), besides the environmental advantages to *in-situ* recycling, cold in-place recycling can be used on pavements that have developed severe cracks but no structural failure. Unlike hot in-place recycling, it is not limited to pavements exhibiting only surface defects. The cold mix tends to be self-healing and therefore helps to retard reflection cracking and localised roughness.

3.2.3 Cold in-plant recycling

In the cold in-plant recycling method the recycling is carried out in a central plant where the material is collected from existing pavement and processed, by adding rejuvenators or virgin aggregates with or without recycling agents. Cold-mix recycling generally refers to central plant mixing and is done without heating the materials (Kandhal, 1997). In-plant recycling allows materials from different sources to be selected and pre-treated, which increases confidence in the final product achieved from the process (Wirtgen, 2012). According to Wirtgen, the main benefits of cold in-plant recycling is the control over the input material, quality of mixing and stockpiling capabilities when compared with cold in-place recycling.

Cold in-plant recycling is a similar process to the hot central plant mixing, except it does not involve any heating, and therefore emulsion bitumen is used as a binder in most cases. Precise control over the mixing time is important; over-mixing may cause premature breaking of emulsified bitumen, under-mixing results in insufficient coating of aggregates. One of the material sources for cold in-plant processing can be RAP material from a cold planning operation, provided that proper material characterisation and material mix design is carried out.

3.2.4 Hot in-place recycling

In 2001 the AARA defined hot in-place recycling as an on-site, in-place rehabilitation method which consists of heating, softening, scarifying, mixing, placing, and compacting the existing pavement. Virgin aggregates, asphalt binder, recycling agents, and/or new HMA can be added,

on an as-required basis, to improve the characteristics of the existing pavement. Virgin aggregates or new HMA which is incorporated into the HIR process is commonly referred to as "admix". With HIR, one hundred percent of the recycling of the existing asphalt pavement is completed on site. The process consists of heating and softening the existing asphalt pavement, permitting it to be scarified or hot rotary milled to the specified depth. The scarified or loosened asphalt pavement is then thoroughly mixed and subsequently placed and compacted with conventional HMA paving equipment (ARRA, 2001). It improves the pavement condition, minimises traffic disruptions and short lane closures, and provides an economical method for pavement preservation.

3.2.5 Hot in-plant recycling

Hot in-plant asphalt pavement recycling is a method where the reclaimed asphalt pavement (RAP) material is processed, mixed with virgin materials in a central plant to produce hot mix asphalt (HMA). The RAP materials can be obtained from cold milling using a rotary drum milling machine or from removed asphalt pavement by a crushing or ripping operation (Kandhal, 1997). Where the RAP material is obtained from different sources and stock-piled in a central location to be used in the production of hot mix asphalt, it is processed into a courser granular material by limiting the amount of fines before it is used in the mixing process. For the processing of RAP materials, a crusher with a screening unit and stackers are used on site (FHWA, 2016). It is useful in the conservation of non-renewable resources and energy while providing the same performance as pavements constructed with one hundred percent new materials.

In the central mixing plant for asphalt pavement recycling, either specially designed plant or modified hot mix plant can be used where the process follows a heat transfer method to soften the RAP material to allow for easy mixing with virgin materials (ARRA, 2001). The hot in-plant recycling method enables better control of the input materials into the plant and produces a good quality hot mix. Hot in-plant recycling is the most widely used method, where about 33% of the RAP generated is used in hot recycling plants in the USA only (ARRA, 2001).

3.2.6 Full depth reclamation

Full depth reclamation is the rehabilitation technique in which the full thickness of the asphalt pavement and a predetermined portion of the underlying materials (base, sub-base and/or sub-grade) is uniformly pulverised and blended to provide an upgraded, homogenous base material (ARRA, 2001). This type of recycling technique for pavement construction and rehabilitation has gained general recognition because of the technical, economic and environmental advantages (Bocci et al., 2014).

In the FDR rehabilitation process the pavement can be milled 150–350 mm depth, mixed with new bitumen and existing material to form a uniform and strengthened pavement structure. It was also indicated by (EAPA, 2014) that hydraulic binders are added creating hydraulically bound or cement bound mixes (HBM and CBM) of 100% recycled aggregates.

Study	Discussion
• ARRA, 2001. • Kandhal and Mallick, 1997. • Zumanis, M., Mallic, R.B., Frank, R., 2014. • Chen, D., 2006. • Shuling Tang, Yuejian Cao, and Joseph F. Labuz, 2012. • Jitareekul, P., 2009. • Chen, D., and Jahren, C., 2007. • Eddie, N. J., and Roger, O., 2009. • Sanjeevan S., Piratheepan M., Hajj, E. Y., and Bush A. K., 2014. • Suleiman, N., 2002. • David Jones, Rongzong Wu, and Stefan Louw, 2015. • David Jones, Stefan Louw, and Rongzong Wu, 2016. • Diefenderfer, et al., 2016. • Thomas, J.K., et al., 1992. • Inhwan Kim, 2014. • Pérez, I., Pasandin, A.R., and Medina, 2012. • Esenwa, et al., 2013. • Warren H. Chesner, Christopher W. Stein, Henry G. Justus, Edward R. Kearney, and Stephen A. Cross, 2011. • Al Qadi, et al., 2012. • Becca Lane and Tom Kazmierowski, 2012. • Brian K. Diefenderfer and Alex K. Apeagyei, 2011. • Shoenberger, 1992. • Clinton I.V.W., 2014. • Luke Johanneck and Shongtao Dai, 2013. • T. Anil Pradyumna, Abhishek Mittal, P.K. Jain, 2013. • Copland, A., 2011. • Holt, C., et al., 2009. • Mallela, H.L., et al., 2006. • Randy C. W., et al., 2009. • Robert, L., 2009. • Thomas, T. & Kadrmas, A., 2002.	All the literature advocates these benefits in one way or another: • cost effective • environmentally friendly • energy saving • conservation of natural resources It could be only for one of the recycling methods or can be for all recycling types that the benefits are indicated. In some cases, only one of the benefits is mentioned, while in many cases all of the above indicated benefits are mentioned as a common advantage obtained from recycling asphalt pavements. Detailed benefits are mentioned in many of the studies and are shown in this research work. It is left out from this to avoid duplication.

Table 3-1 Literature discussed about benefits of recycling

Study	Discussion
• Thomas, T. & Kadrmas, A., 2002. • Jang, Y.I., et al., 2015. • Kamran Muzaffar Khan, et al., 2012. • Fujie Zhou and Cindy Estakhri, 2013. • Nantung, T.E., Ji, Y., and Shields, T., 2011. • Bocci, M., et al., 2014. • Per Gosta, et al., 2012. • Carvalho, et al., 2010. • Praduman, T.A., et al, 2013. • Susan Chan, et al., 2009. • Wirtgen, 2012. • Heather J. Miller, Maureen A. Kestler, Meghan Amatrudo, Robert Eaton, and Andrew Hall, 2011. • Kang-Won, W.L., & Muller, M., 2014.	

3.3 Systematic literature review

The methodology adopted for the systematic review is summarised in Figure 3-1

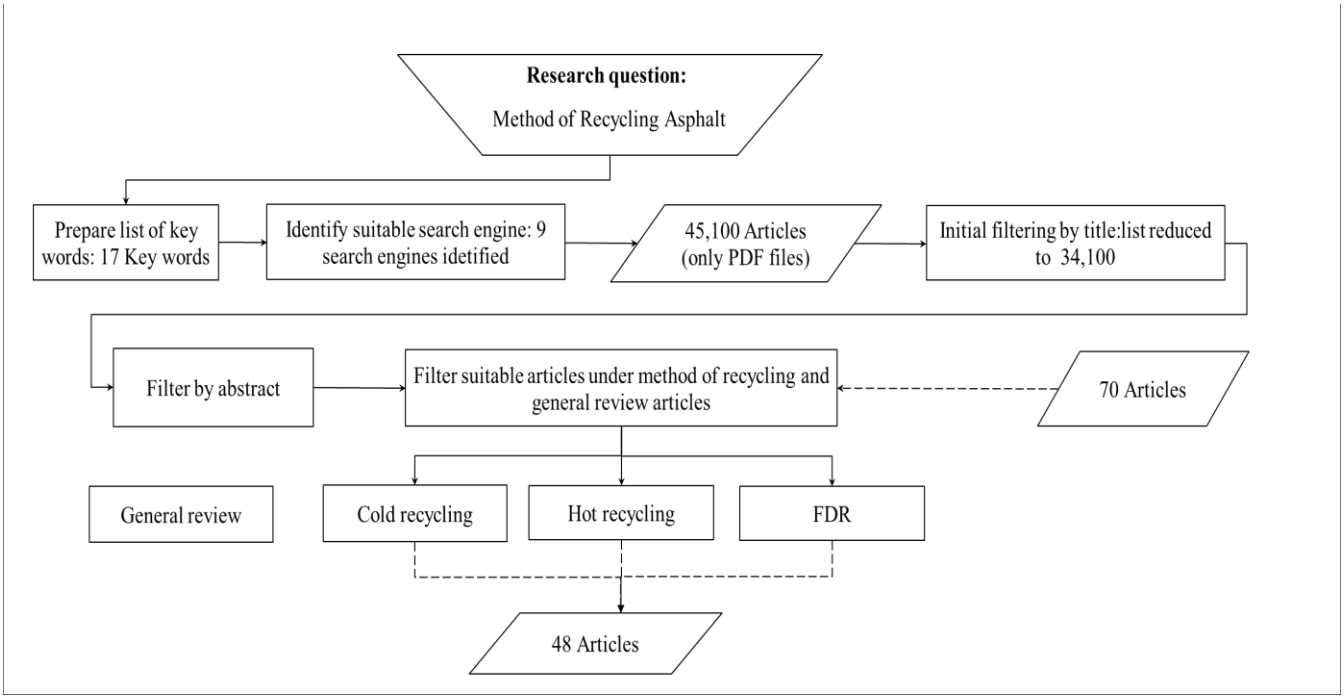


Figure 3-1 Systematic Literature review process

3.3.1 Literature search and selection

In order to search for relevant literature systematically it is important to select appropriate key words. Accordingly, for this research a list of key words that were used to search for the literature was developed as follows.

i. Recycling in road construction
ii. Recycling of pavement materials
iii. Reuse of pavement materials
iv. Regenerating pavements
v. Durability of recycled materials
vi. Durability of recycled unbound materials in roads
vii. Durability
viii. Unbound recycled materials in roads
ix. Industrial waste in roads
x. Granular materials for roads
xi. Marginal road construction materials
xii. Stabilisation of soils
xiii. Soft aggregates in roads
xiv. Waste material in road construction
xv. Manmade materials in roads
xvi. Full depth reclamation
xvii. Cold recycling of pavements
xviii. Reuse of asphalt
xix. Reuse of asphalt in road maintenance
xx. Reuse of asphalt in new road construction
xxi. Old asphalt
xxii. Sustainable asphalt
xxiii. Environmental impact of asphalt
xxiv. Asphalt disposal
xxv. Asphalt in topical roads
xxvi. Durability of asphalt

xxvii. Reuse of asphalt in hot climate

xxviii. Effect of heat and humidity on asphalt

3.3.2 Identifying and defining relevant studies: applying inclusion/exclusion criteria

In the process of identifying the relevant studies for this research, criteria were developed as to which type of literature shall be included in the study. Accordingly, the inclusion or exclusion criteria used and their definitions are presented as follows. Much literature is available on asphalt pavement recycling. Using key words, the number of literature studies found were 45,100. Out of these, 48 works were selected for the purpose of this research, with 12 of them focusing on cold recycling of asphalt pavements. The details of the process used to select these literature studies are shown in Figure 3-1. The criteria developed for the inclusion/exclusion of the literature are as follows.

3.4.2.1 Inclusion criteria

The criteria used in the selection of the most relevant literature for the study of cold Reclaimed Asphalt Pavement materials are:

i. Cold and hot Reclaimed Asphalt Pavement and FDR related literature
ii. Journals, reports, manuals and conference proceedings only
iii. Literature based on field performance evaluation of Reclaimed Asphalt Pavement materials
iv. Literature based on laboratory investigation of recycled asphalt materials
v. Publications published after 1960

Reclaimed Asphalt Pavement materials in general will be considered, however, more focus is on cold recycling of asphalt pavement methods. In order to select and recommend the most appropriate recycling technology that can be applicable in local conditions, the performance of the recycled materials evaluated in other areas are reviewed and analysed.

Books are more general and may not show specific study results that can be used as a reference for this study. Data may also not be available in books to make comparisons and analysis to see performances from different studies. On the other hand, journals and conference proceedings are more specific studies with data that can be extracted and analysed. Therefore, journals that are

written on asphalt pavement recycling and with performance evaluation information were selected. Specific research showing performance evaluation results from trial sections for medium or long term (three to ten years) was preferred as reference literature for this study.

In order to better understand the performance and appropriateness of Reclaimed Asphalt Pavement materials, the literature based on continuous evaluations of trial sections was reviewed. Literature that was not based on performance evaluation was used for understanding theoretical aspects and as background information for this research. The focus was on extracting performance data and analysing to see how the Reclaimed Asphalt Pavement materials perform in different conditions.

A trial section construction is based on laboratory investigation results. After many tests in the lab, most optimum mix designs are selected for performance evaluation through construction of trial sections and continuous monitoring. Samples from the trial section are also collected and investigated in labs and results are documented. Laboratory investigations give very good information about the performance of various mix designs and the procedures required for the preparation, mixing and testing of Reclaimed Asphalt Pavement materials.

Asphalt pavement recycling is not a new technology and dates back to 1915. It has been practiced in different parts of the world for a long time. However, recent studies have been selected to evaluate the technology based on recent developments that can be easily transferred to practice in Ethiopia. It is also good to understand the current technological developments that are used in the asphalt pavement recycling practices so that the gap can easily be identified. Older documents are also consulted to get an historical background. Accordingly, journals, research results and conference proceedings produced after the year 1960are used in this research work.

3.4.2.2 Exclusion criteria

All literature excluded from the list is based on the following exclusion criteria:

i. Literature published before the year 1960
ii. Literature without performance evaluations in the laboratory and on field trial sections

iii. Books and power point presentations. As described in the inclusion criteria, the excluded literature is that which may not be helpful in data extraction and analysis of laboratory and field performance.

3.3.3 Review question and approach

A literature review is carried out systematically to fully understand what asphalt pavement recycling technology is and how it can be applied to local conditions in Ethiopia. By addressing the research questions shown in section 2.2, one can appropriately and correctly characterise properties of recycled materials for their maximum benefit in terms of performance of pavements constructed using the recycling technology.

3.3.4 Studies included in the review/synthesis

Using search criteria and procedures for relevant literature, more than 45,100 can be identified, which are further screened and refined. The screening was done manually using the inclusion/exclusion criteria and full text availability on the web or in other sources such as libraries. Accordingly, the number of studies was further reduced to 34,000 and further screened by their titles, abstracts and type of publications. The final number of literature studies was then 483 that were considered relevant to asphalt pavement recycling in general. All the studies were then put in to Microsoft Excel to further screen, categorise and map them, and also to remove duplicates.

Some 11,000 (24%) articles were removed as they were totally irrelevant to this research on the first stage. In the next screening those only relevant to recycling technology for asphalt pavements were selected based on their availability (either in pdf format or in hard copy), type of publication (whether it is a journal, conference paper, report etc.). It was found that 59 articles were focused on cold recycling technology and were selected or included in the study; while only 12 articles were found to be focusing on performance evaluation of cold asphalt recycling including full depth reclamation.

The articles were further summarised and mapped based on their sources, type and year of publication. The type of articles found covered a wide range from PowerPoint presentations to reports and journals. The journals, reports, conference papers and thesis papers scored the highest numbers; while the journals constituted 52%, which is the highest number in the list.

Reports scored 16.4%, while conference papers were 12.2% of the collected studies. Therefore, it can be seen the studies included are mostly journals, reports and conference papers. The following graph (Figure 3-2) shows the distribution of the studies based on the type of publication.

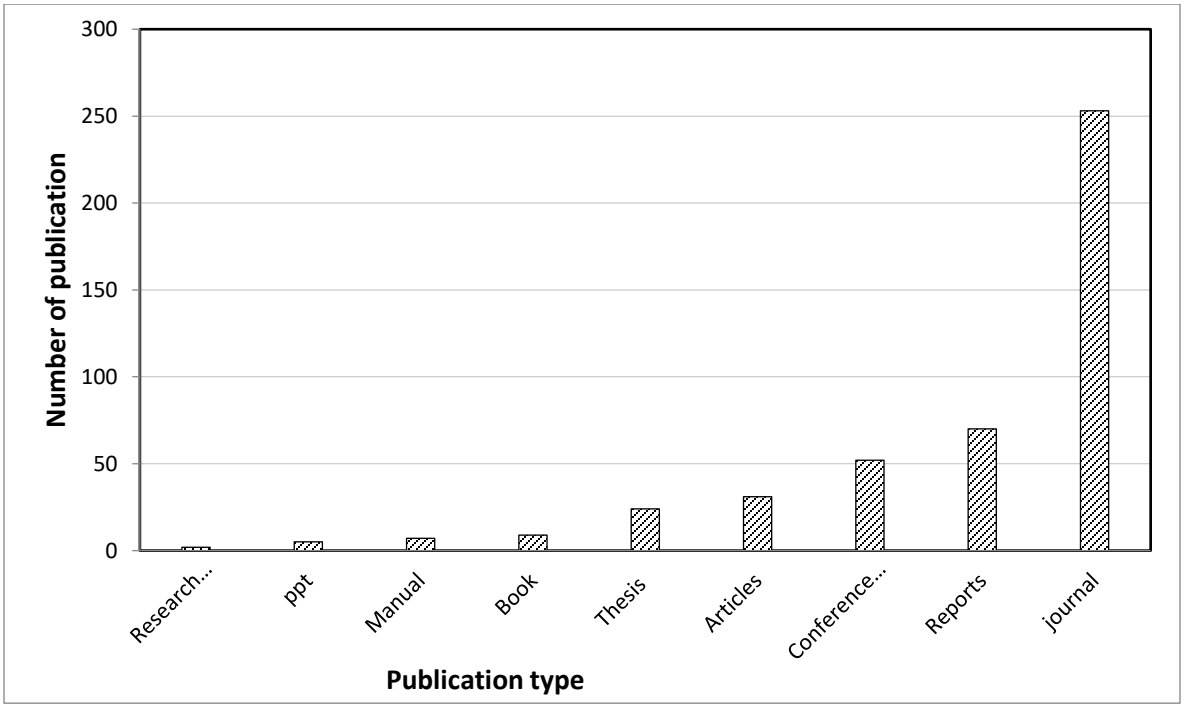


Figure 3-2 Number of publications by type

The year of publication of most of the studies obtained was after the year 2000, which accounts for 89% and indicates more research has been conducted recently. Only 10.3% of the studies were published between 1970 and 2000. The literature published before 1970 was only 0.5% of the studies identified in the search process. It is also interesting to note that the majority of the works were carried out after 2010 (52% out of the 89% since 2000), which indicates that asphalt pavement recycling is becoming more popular in recent years among the researchers and professionals. This can be associated with the issues such as resources are becoming scarcer and more expensive, and more technological improvements have been made in asphalt pavement recycling.

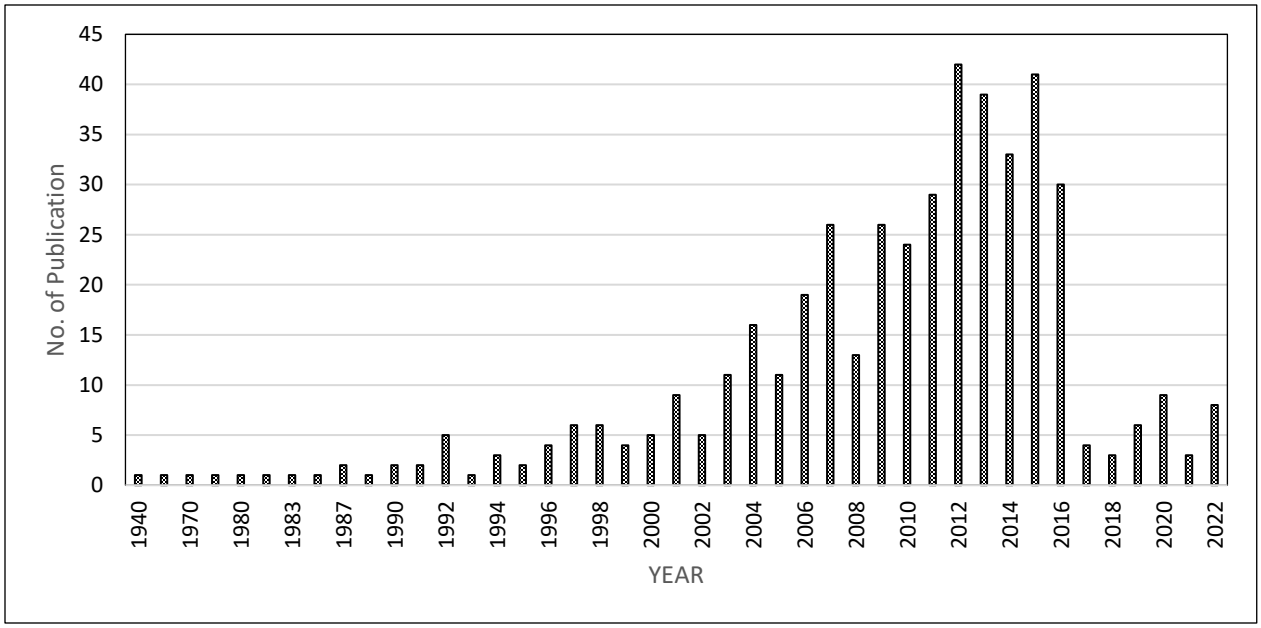


Figure 3-3 Number of publications by year

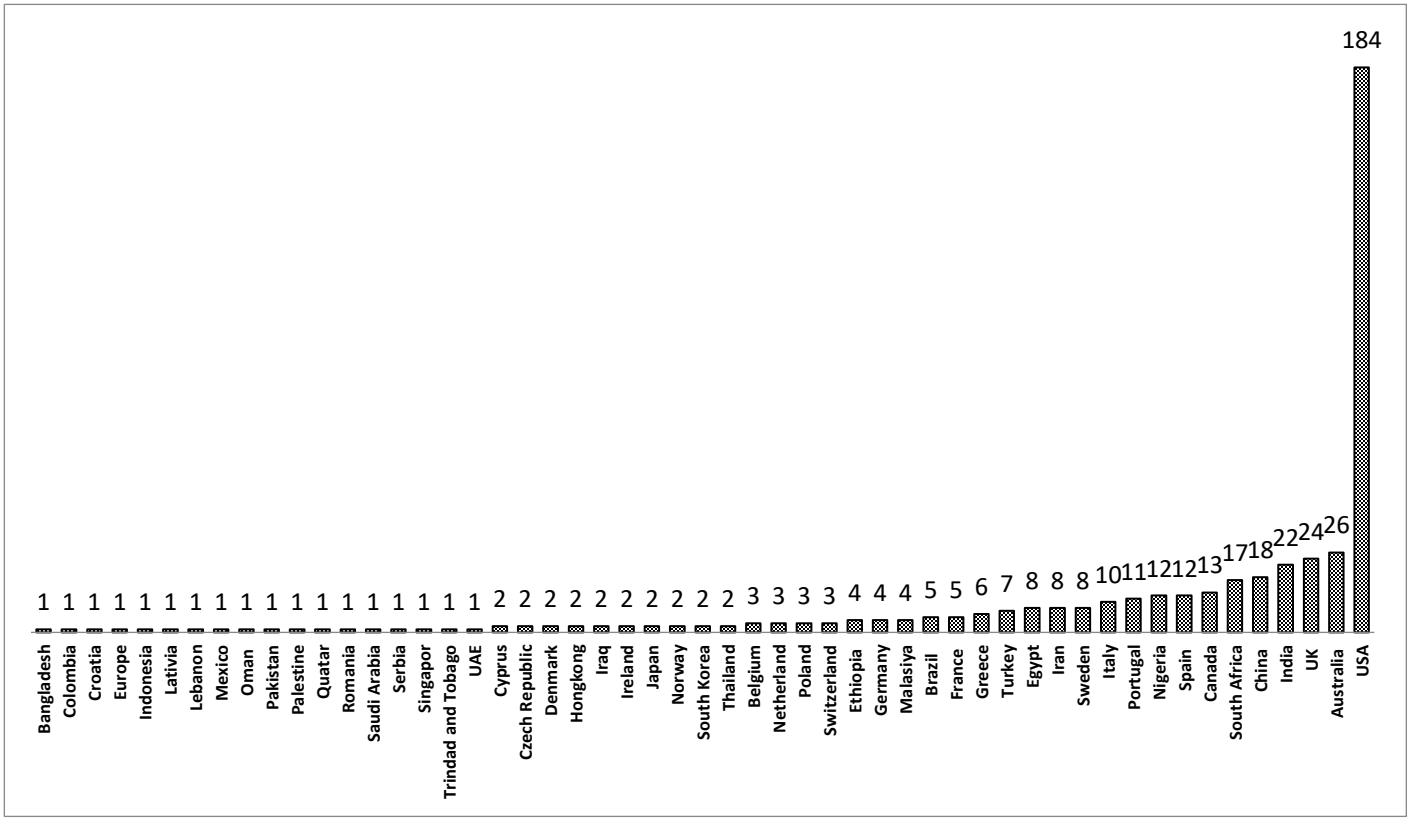


Figure 3-4 Number of publications by country of origin

The USA has contributed significantly to the asphalt pavement recycling technology research. Out of the 51 countries from where the studies were collected, 39.4% were from the USA. This can also be seen from the difference between the USA and the second contributor Australia, which has contributed only 6.1%. The major contributors were USA, Australia, United Kingdom, India, South Africa, Spain, Nigeria, Canada, Portugal and China. The graph in Figure 3.4 indicates the distribution of publications based on their country of origin. The graph is shown for the top 10 countries only.

3.4 In-depth review of studies

The process of identifying and selecting the studies to be included in this research resulted in 42 studies. These studies were used in the review process for the recycling of pavements giving emphasis on cold recycling and full depth reclamation. These studies were selected based on analysis of the weight of evidence where they were evaluated on how well they can respond to the research questions.

These are the questions addressed through this research. Accordingly, based on the checklist developed to weight the soundness, appropriateness to answer the review questions, and relevance of the study focus, (Burrow, 2016) 42 studies were selected to be included in this research.

3.4.1 Assessing quality of the literature

The studies were selected by evaluating them in the search process by allocating a ranking of high, medium and low. Values were given to these ratings as 1.0 for high, 0.67 for medium and 0.33 for low. Those who had a total score above 3.0 (>3.0) were selected. There were five assessment criteria used to evaluate the studies and accordingly the highest value one study could score was 5.0. The final marking was given based on the score each of the studies were given for the five assessment criteria as shown in Table 2.1. The score was given to each study for each of the assessment criteria and then summed up to get the final score.

Accordingly, 13 studies focus on cold in-place (CIR), 19 studies on general (includes all the three cold recycling technologies, CIR, FDR, Cold In-Plant), 5 studies on cold recycling and 4 studies on FDR as shown in Table 3.2.

Publications complying with the selection criteria were grouped in terms of recycling type and areas considered: cost effectiveness, environmental sustainability, ease of construction, energy saving, economic sustainability, minimal use of virgin materials, suitable for labour intensive work, suitability for different climatic conditions, suitability for small-scale contractor and suitability for low volume roads, as shown in Figure 3-5 and Appendix A. None of the 38 studies, discussed the suitability for low volume roads and suitability for small-scale contractor, and only one study related to the different climatic conditions. Suitability for different climatic conditions was discussed by only two studies. Cost effectiveness, environmental sustainability and energy conservation were addressed in many publications.

Cold in-place and cold in-plant techniques were the most discussed techniques, suggesting that these are possibly the most favoured techniques as shown Table 3-3.

Table 3-2 Studies grouped based on recycling types and areas of the criteria

	Cost Effectivness	Environmental Suitability	Ease of Construction	Energy Saving	Economic Suitability	Minimized use of Virgin Materials	Suitability for Low Volume Roads
CIR	Kilpatrick, 2009 Prithvi S Kandhal, 1997 Don Chen, 2007 Jitreekul, 2009 Horvath, 2003 Gerardu and Hendriks, 1985 Kazmirowski and Reymond, 1992 Kim, 2014 Imad L Alqadi, 2014 Paulo Pereira, 2006 Michael Essenwa, 2013 Christopher Holt, 2009 Kamran Muzaffar Khan, 2012	Kilpatrick, 2009 Prithvi S Kandhal, 1997 Zumanis et al , 2014 Don Chen, 2007 Jitreekul, 2009 Kazmirowski and Reymond, 1992 Kim, 2014 NCHRP, 2011 Paulo Pereira, 2006 Andrew E Alkins, 2008 Lee et al , 2010 Kang Won Wayne Lee, 2014	Prithvi S Kandhal, 1997 Don Chen, 2007 Kazmirowski and Reymond, 1992 NCHRP, 2011 Writgen, 2010	Prithvi S Kandhal, 1997 Don Chen, 2007 Jitreekul, 2009 Gerardu and Hendriks, 1985 Kazmirowski and Reymond, 1992 Kim, 2014 NCHRP, 2011 Paulo Pereira, 2006 Michael Essenwa, 2013 Lee et al , 2010 Kang Won Wayne Lee, 2014 D Merrill, 2004	Kilpatrick, 2009 Prithvi S Kandhal, 1997 Don Chen, 2007 Jitreekul, 2009 NCHRP, 2011 Paulo Pereira, 2006 Michael Essenwa, 2013	Prithvi S Kandhal, 1997 Don Chen, 2007 Jitreekul, 2009 Kim, 2014 NCHRP, 2011 Paulo Pereira, 2006 Andrew E Alkins, 2008 Copland A , 2011	Michael Essenwa, 2013
Cold In-Plant	Prithvi S Kandhal, 1997 Byrne, 2005 Horvath, 2003 Gerardu and Hendriks, 1985 Brian K Diefenerfer, 2016 Kim, 2014 Paulo Pereira, 2006 Randy West, 2009 Lee et al , 2010	Horvath, 2003 Kim, 2014 Randy West, 2009 Lee et al , 2010 Susanne Chan, 2009		Prithvi S Kandhal, 1997 Byrne, 2005 Gerardu and Hendriks, 1985 Kim, 2014 Randy West, 2009	Lee et al , 2010 Susanne Chan, 2009 D Merrill, 2004	Brian K Diefenerfer, 2016 Kim, 2014 Randy West, 2009 Locander, 2009	
HIR	Prithvi S Kandhal, 1997 Gerardu and Hendriks, 1985 Lee et al , 2010	Prithvi S Kandhal, 1997 NCHRP, 2011	Prithvi S Kandhal, 1997 NCHRP, 2011 Copland A , 2011				
Hot In-Plant	Byrne, 2005 Gerardu and Hendriks, 1985 Paulo Pereira, 2006 Lee et al , 2010	Prithvi S Kandhal, 1997 Byrne, 2005 Lee et al , 2010	Prithvi S Kandhal, 1997	Byrne, 2005 Gerardu and Hendriks, 1985 Lee et al , 2010	Prithvi S Kandhal, 1997	Prithvi S Kandhal, 1997 Byrne, 2005	
FDR	Prithvi S Kandhal, 1997 Shuling Tang, 2012 Brian K Diefenerfer, 2016 NCHRP, 2011 Bocci et Al , 2014 Writgen, 2010	Prithvi S Kandhal, 1997 Christopher Holt, 2009 Bocci et Al , 2014 Writgen, 2010	Prithvi S Kandhal, 1997	Prithvi S Kandhal, 1997 Christopher Holt, 2009 Writgen, 2010	Prithvi S Kandhal, 1997 Shuling Tang, 2012 Christopher Holt, 2009 Writgen, 2010	Prithvi S Kandhal, 1997 Shuling Tang, 2012 Christopher Holt, 2009	Bocci et Al , 2014

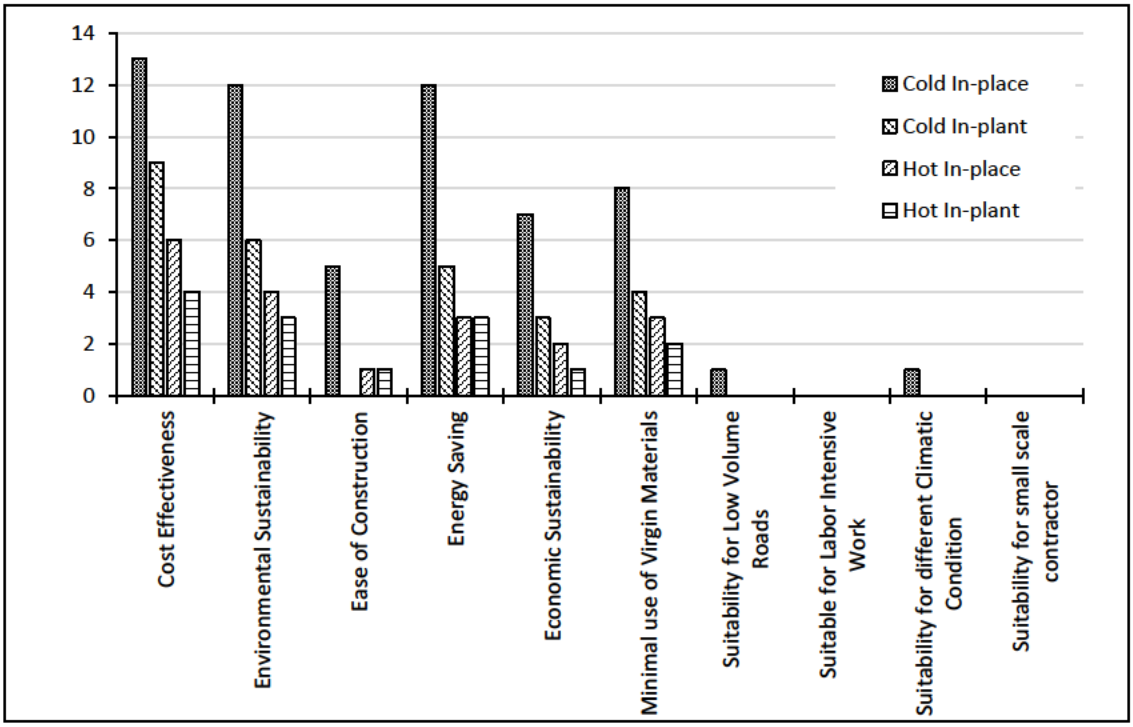


Figure 3-5 Number of studies and suitability evaluation criteria

All the treatment options are extensively described in the various literature. A brief description of treatment options together with their benefits and limitations are given in Table 3-3.

Table 3-3 Benefits and limitations of recycling methods

Technique	Description	Benefit	Limitations
Cold In-place Recycling (CIR)	Comprises milling the existing asphalt, mixing it with a proportion of new aggregate and bitumen emulsion before placing it and applying compaction to form the new road surface. ([1])	• Low greenhouse gas (GHG) emissions and thus reduced global warming impact. • No need to preheat the asphalt before placement. • All the milled asphalt is reused in the new road construction. • Most of the savings are associated with the reduction in hauling of materials, waste disposal to landfills and minimised use of virgin materials. Using CIR can result in cost savings of between 30 to 55% compared to HMA. • It is highly cost effective, environmentally friendly and energy efficient ([2])	• May not be feasible for low-volume roads' rehabilitation except perhaps in remote and isolated areas where plant-produced hot mix cannot be applicable due to long haul and losing its temperature. ([3]) • CIR is highly mechanised and requires specialised plant and skilled operators. • Difficult for small-scale contractors. • Not labour intensive. • Although smaller machines are available, this technique can involve long trains which may not be suitable for local residential streets with very limited space for manoeuvring of equipment.
Cold In-plant Recycling	Milled asphalt is collected and stock-piled in a central location, where it is processed and mixed with new aggregate and bitumen in a plant before dispatching to site. This ensures better quality control and	• Potentially better-quality control in manufacture compared to CIR as it is centrally processed. • No wastage as potentially all the milled asphalt can be reused. • Old, stockpiled asphalt can be used. • Overall energy saving as reduced need for	• Some environmental impact related to haulage of milled and processed asphalt. • Not easy operation. • Contamination as RAP materials can be collected from different sources and stockpiled together, • High material variability as it is collected

	results in a more homogeneous mix, which can be cost effective in the long run, saves energy, and is economically sustainable. ([4]) Cold in-plant method of recycling can be a better choice where asphalt pavements are demolished and stock-piled for immediate or future use.	virgin materials and no need for disposal. • No processing required prior to recycling operation. • Cost savings. • Reduced environmental impact. • High proportion of RAP (30 to 80%) may be used. • Reduced whole life costs – 21% lower than using conventional asphalt. • Generally, it provides high-cost savings and is environmentally sustainable. Has also benefit in saving energy and minimises use of virgin materials such as crushed stone. ([5])	from different sources and stockpiled together. • May not be feasible for low-volume roads' rehabilitation.
Hot In-place Recycling (HIR)	It can be done as different types: such as heating and scarification of existing pavement, add rejuvenator, level and compact; or mill and remix, add rejuvenator, level and compact; or mill, remix with additional aggregate or asphalt mix, level and compact. ([6])	• Work can be completed in a single pass so that traffic disruption is minimum. • Substantial cost savings between 17% and 50% ([7]) • 20% - 30% savings in construction time. • Cheaper compared to HMA as it fully utilises existing pavement materials. • Environmentally friendly as no new excavation is required for virgin materials and easy to implement. ([8])	• It is applicable only for asphalt concrete pavements. • Only the top 50 mm can be recycled to address minor pavement damages. • Not suitable for deep rutting. • Surface treated pavements may not be good candidates for this type of recycling.

Hot In-plant Recycling	Has similar process to that of conventional HMA production but with RAP replacing a proportion of a virgin material. Material for recycling is obtained through cold milling or ripping and crushing from existing pavement. ([9])	• Has cost reduction up to 20% to 30%. • Environmental and energy benefits mainly due to the reuse of old asphalt. • Energy saving due to reduced mixing time in the plant. • Reduces the cost of disposal of old materials. • Gives cost savings due to reduction in using virgin materials. • Equal or better results than that of 100% virgin mix. • RAP materials can be used in high proportion in HMA mix preparation. • Allows for better control of input materials in to the plant and produces good quality mix. ([10])	• Need crusher with screen on asphalt plant site to process the RAP materials. • May need modification of central asphalt mixing plant or specially designed plant for heating to easily soften RAP material.
Full Depth Reclamation	Full thickness of the asphalt pavement along with a certain portion of base course can be milled, stabilised and re-compacted at the same time. It is basically a cold in-place process. ([11])	• It is environmentally friendly, economically sustainable, and uses fewer virgin materials. • It is an attractive alternative where resources are conserved, eliminates waste disposal, material and transportation costs are reduced. • In the process of reclamation air quality is not affected due to fumes, dust and smoke. • CO_2 emission is reduced by 27% from the	• In this method lack of control of depth of cutting, there is a need for trained personnel and specialised equipment, especially for low-volume roads' rehabilitation. • Traffic control problems.

		material production and transportation. • Overall energy consumed by FDR is lower compared to the traditional rehabilitation technique. ([12]) • May be used in the construction of rural roads where the pavement is severely damaged and riding quality is seriously compromised.	

(1) (Kilpatrick, 2009); (Kandhal, 1997); (Chen, 2007); (Jitareekul, 2009); (Horvath, 2004); (Gerardu, 1985); (Kazmierowski, 1992); (Kim, 2014); (Al-Qadi et al., 2014); (Pereira, 2006); (Essenwa, 2013); (Holt et al., 2009); (Khan, 2012); (Zaumanis, 2014); (NCHRP, 2011); (Alkins, 2008); (Lee, 2010); (Lee, 2014); (Writgen, 2010); (Merrill, 2004); (Copland, 2011)

(2) (Kilpatrick, 2009); (Kandhal, 1997); (Chen, 2007); (Jitareekul, 2009); (Horvath, 2003); (Gerardu, 1985); (Kazmierowski, 1992); (Kim, 2014), (Al-Qadi et al., 2014), (Pereira, 2006); (Essenwa, 2013); (Khan, 2012); (Kilpatrick, 2009); (Zaumanis, 2014); (NCHRP, 2011); (Alkins, 2008); (Lee, 2010); (Lee, 2014)

(3) (Essenwa, 2013)

(4) (Kandhal, 1997); (Byrne, 2005); (Horvath, 2003); (Gerardu, 1985); (Diefenerfer, 2016); (Kim, 2014); (Pereira, 2006); (West, 2009); (Lee, 2010); (Chan, 2009); (Merrill, 2004); (Locander, 2009)

(5) (Kandhal, 1997); (Byrne, 2005); (Horvath, 2003); (Gerardu, 1985); (Diefenerfer, 2016); (Kim, 2014); (Pereira, 2006); (West, 2009); (Lee, 2010); (Horvath, 2003); (Kim, 2014); (West, 2009); (Lee, 2010)

(6) (Kandhal, 1997); (Gerardu, 1985); (Lee, 2010); (NCHRP, 2011); (Copland, 2011)

(7) (Kandhal, 1997); (Gerardu, 1985); (Lee, 2010)

(8) (Kandhal, 1997); (NCHRP, 2011); (Copland, 2011)

(9) (Byrne, 2005); (Gerardu, 1985); (Pereira, 2006); (Lee, 2010); (Kandhal, 1997)

(10) (Byrne, 2005); (Gerardu, 1985); (Pereira, 2006); (Lee, 2010)

(11) (Kandhal, 1997); (Tang, et al., 2012); (Diefenerfer, 2016); (NCHRP, 2011); (Bocci et al., 2014), (Writgen, 2010); (Holt et al., 2009)

(12) (Kandhal, 1997); (Tang, et al., 2012); (Diefenerfer, 2016), 2016; (NCHRP, 2011); (Bocci et al., 2014); (Writgen, 2010); (Holt et al., 2009)

3.5 Overview of asphalt pavement recycling

As the size of the road network in Ethiopia is continually increasing it is vital to keep it in a serviceable condition. This is especially important in the areas where there is shortage of virgin aggregates, as the issue of maintenance and rehabilitation becomes critical. Natural resources can become depleted and there is a negative impact on the environment when virgin materials are constantly used for road construction and maintenance. Recycling or reusing the existing pavement material for the rehabilitation of roads will significantly help in addressing the shortage of good quality materials and minimising the adverse environmental impact.

In Ethiopia more emphasis is given to the construction of new roads and less attention to maintenance of the existing road pavements. Additionally, maintenance is also carried out using the conventional method employed for new construction, which may be suitable for rehabilitation and maintenance; however, it is a very slow process. It is particularly challenging to work during heavy traffic, and is relatively inefficient in not making use of the *in-situ* material from the existing pavement (Lewis, 1999). Recycling and reusing materials from the existing pavement are now becoming more attractive and are considered better alternatives.

The recycling or reuse of pavement material is a very simple but effective concept and dates back to 1915 (Kandhal, 1997). The existing degraded pavement is improved and transformed into a homogeneous structure that can support the traffic requirements (PIARC 2003). The Romans are thought to have been the first to develop recycling technology more than 1900 years ago (Richardson and Jordan, 1994). The first documented case of asphalt recycling, in the form of Hot In-Place Recycling (HIR), was also reported in the literature of the 1930s (ARRA, 2001).. However, only moderate advancements due to limited resources in asphalt recycling technology and equipment occurred until the mid-1970s (ARRA, 2001).

According to (ARRA, 2001), two major events in the 1970s led to the further development of asphalt pavement recycling. The first was the petroleum crisis and the development and introduction in 1975 of large-scale cold planning equipment. Since then, asphalt recycling methods and technologies have advanced exponentially due to the efforts of the equipment manufacturing and construction industries (ARRA, 2001). Another event which helped to

enhance and improve asphalt pavement recycling was in early 2000 when the cost of oil significantly increased and there was a shortage of good quality aggregate (Esenwa et al., 2013).

Much research has been conducted in many countries in recent years to maximise the benefit of asphalt pavement recycling. Interest in using RAP materials has increased mainly due to its cost saving and increased environmental awareness (Al-Qadi et al., 2014).

In 2015 the estimated tons of RAP used in asphalt mixes in the USA reached 74.2 million, according to the 6th annual survey on the use of recycled materials and warm-mix asphalt by NAPA (Hanson, 2015). The amount of savings gained from recycling existing pavement is significant, and due to that the amount of pavement maintenance expenditure may be increased. The combined saving of asphalt binder and aggregate by using RAP and RAS in asphalt mixes is more than $2.8 billion. This keeps asphalt pavement mixture costs competitive and allows owners to achieve more roadway maintenance and construction activities within limited budgets (Hanson, 2015).

The recycling of asphalt pavements is a beneficial for technical, economical, and environmental reasons and the use of recycled asphalt pavements has been selected over virgin materials due to the increasing cost of asphalt, the scarcity of the quality aggregates, and the pressing need to preserve the environment. Therefore, recycling of the existing asphalt pavement materials should be explored to create a sustainable pavement system.

3.6 Synthesis: Reclaimed Asphalt Pavement (RAP) materials

Asphalt pavement recycling has been carried out for many years since its inception around 1915 and is becoming more popular nowadays with the diminishing of the natural resources required for the construction and maintenance of roads. The need for recycling is more pronounced as aggregate production is becoming more expensive and the impact on the environment is becoming more considerable. In addition, the ever-increasing cost of bitumen is making road construction and maintenance more and more expensive. Thus, reclaiming asphalt pavement materials as a source for maintenance and rehabilitation is now considered economical and environmentally friendly.

Reclaimed asphalt pavement (RAP) materials obtained from deteriorated asphalt pavement can be used in asphalt surfacing and in base and sub-base courses. Additionally, RAP can be used in gravel roads as a wearing course.

Understanding the behaviour of RAP material is key to using it in an efficient way in rehabilitation projects. The physical and mechanical properties of aggregates from RAP and extracted binders are usually subjects of interest, to be analysed to properly characterise the RAP materials. Production and handling of RAP materials is also an area of concern. In this chapter, background information on RAP materials that help to better understand its properties, handling and its use is assessed and presented.

3.6.1 Production

Reclaimed asphalt pavement (RAP) is a term used to describe material removed from existing deteriorated asphalt pavement during its rehabilitation or reconstruction. Once the asphalt pavement material is removed and processed it becomes RAP material (Hope et al., 2015). The production of RAP materials may not be defined by any standard; however, they can generally be produced either by milling the pavement with a milling machine or the existing pavement is removed in slabs by excavators (Tebaldi, 2012). The removed slabs may be processed in a crushing plant, fractionated and stock-piled either for cold or hot plant asphalt mixing.

The cold planning process also produces RAP materials that can be used for central plant mixing; while in the case of the cold in-place recycling method, the RAP material is milled and reused on site. According to the European Asphalt Pavement Association data (EAPA, 2017), in 2015 a total of 47.3 tons of RAP material was produced in 23 European countries.
The following table shows the total RAP production in Europe in 2015.

Table 3-4 RAP material production in Europe in 2015 (EAPA, 2015)

	Country	All available RAP in tons		Country	All available RAP in tons
1	Australia	1,350,000	13	Lithuania	-
2	Belgium	1,553,994	14	Luxembourg	200,000
3	Czech Republic	2,000,000	15	Netherlands	4,500,000
4	Croatia	-	16	Norway	932,049
5	Denmark	1,300,000	17	Romania	-
6	Finland	1,160,000	18	Slovakia	75,000
7	France	7,000,000	19	Slovenia	37,000
8	Germany	11,000,000	20	Spain	410,000
9	Great Britain	3,500,000	21	Sweden	1,600,000
10	Hungary	180,000	22	Switzerland	-
11	Iceland	15,000	23	Turkey	1,520,000
12	Italy	9,000,000		**Total**	**47,333,043**
				USA	69,700,000

The largest amount of RAP material was produced by Germany (23.2%), while Italy is the second largest producer of RAP material with 19% of the total amount of RAP produced in Europe in 2015. In comparison, in the same year, the USA produced 69.7 million tons of RAP material (EAPA, 2017).

Out of the total amount of RAP produced in Europe about 60% is used in the production of hot mix asphalt. More than 9% is used in the cold recycling and 6.6% goes to the unbound granular road layers. In general, about 70% of RAP material produced from the existing pavement goes back to the road itself.

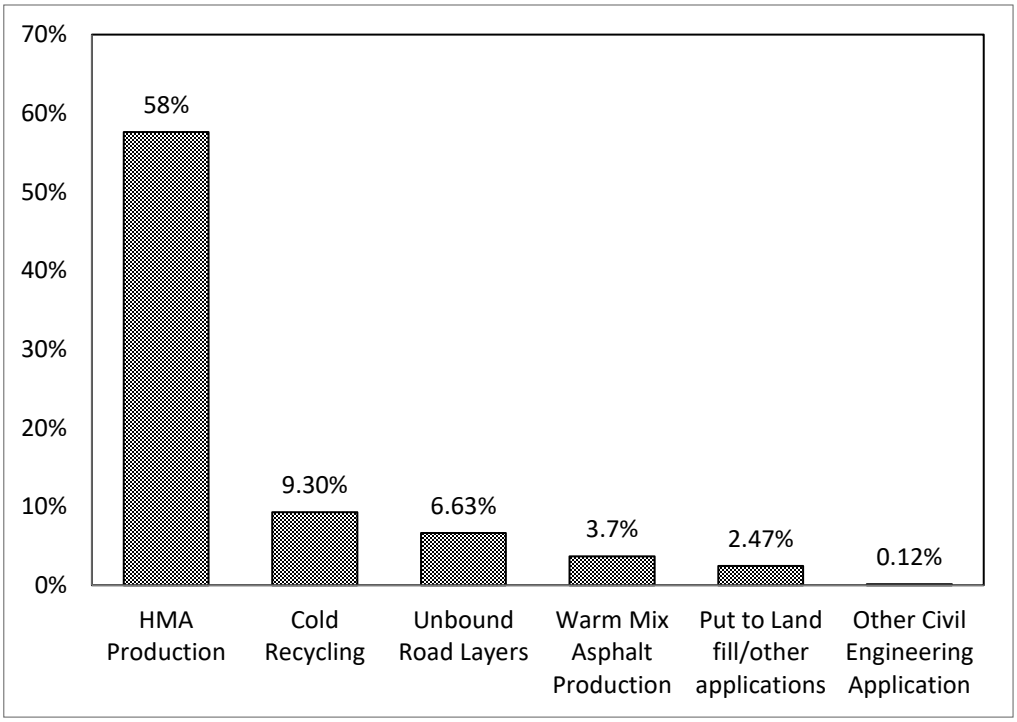


Figure 3-6 Use of RAP (EAPA, 2017)

RAP material produced and not used in the same road is transported to a central stock-piling location for future use. Thus, RAP materials can be collected from different road pavements and sent to stockpiles. In such cases care must be taken to avoid contamination as well as mixing materials with different characteristics. It is important to record details of each load as it arrives to the stock-piling site and make sure that the height of the stockpile is not more than 3 m (Hendriks, 1985). On the other hand, RAP from different sources stockpiled on one site may have an advantage in the process of crushing and screening as it will help in balancing the variation in RAP materials (West, 2009).

A survey conducted in 2015 in the USA (NAPA, 2021) shows that the total estimated amount of RAP stockpiled reached 85.1 million tons. The same study indicated that 74.2 million tons of RAP material was used in asphalt mixes in the year 2015 in the USA. Earlier studies also show that in the US over 90 million tons of asphalt pavement material was reclaimed in the early 1990s (Copland, 2011).

The production of RAP material is the highest in the developed countries, as seen from some studies (EAPA, 2017; NAPA, 2021)while no data could be found during this study that shows the amount of recycled pavement materials in African countries, although some studies show

where there are pavement recycling works, such as in South Africa (Alemayehu & Andrew, 2015; Mhlongo, et al., 2014; Ware, 2006)

3.6.2 Processing

According to the FHWA report the material processing or preparation methods vary for different recycling alternatives. The RAP which is to be used as a granular base is crushed, screened and blended with conventional aggregate (to avoid agglomeration of crushed RAP) and stockpiled. The machinery required also varies from crushers to screens, loaders and stackers. The following table shows the material processing, preparation and required equipment.

Table 3-5 RAP material processing

Activity	**Preparation**	**Equipment**
RAP for Granular Base	Crushing and screening	Primary crusher, screening unit, secondary crusher (optional), conveyers and stacker
	Blending	Cold feed system
	Stockpiling	
	Placement (in-place processing)	Self-propelled pulverising unit
Cold In-plant Recycling	Crushing, screening, stacking and mixing	Crushers, screening unit, conveyers and stacker
Cold In-place Recycling	No prior processing of the material is required	Self-contained continuous train, ripper or scarifier, mixer and rejuvenator feeder
Hot In-plant Recycling	Crushing, screening, stacking and mixing (similar to the cold in-plant)	Crushers, screening unit, conveyers and stacker
Hot In-place Recycling	No need for material processing, except preheating of the pavement surface	Heater, scarifiers, rejuvenator feed, mixer

Processing RAP is carried out to achieve the following basic goals (West, 2010):

- Create a uniform stockpile of material from a collection of different RAP materials from various sources;
- Separate or break apart large agglomerations of RAP particles to a size that can be efficiently heated and broken apart during mixing with the virgin aggregates;
- Reduce the maximum aggregate particle size in the RAP so that the RAP can be used in surface mixes; and
- Minimise the generation of additional P_{200} (i.e., dust).

Since the RAP from a single source is consistent in gradation, aggregate properties and binder properties, processing of it is carried out to separate or break up larger agglomerations so that it can be easily mixed with virgin aggregates, and to reduce the maximum aggregate particle size so that the RAP material can be used in surface mixes (West, 2010). In the case of RAP materials obtained through milling by machine from a single source, further crushing of the material may not be necessary as the gradation is uniform. If necessary, fractionation can be done to separate fine and course particles.

In the case of RAP materials from different sources, processing is carried out to create a uniform and consistent material. As materials from different sources have different gradation and aggregate quality, it is necessary to process them through blending to create uniform gradation and balance the variation in the quality of the aggregates.

According to (West, 2009), there are various types of RAP material processing and each of them has their own advantages or disadvantages. The following table shows the possible advantages and disadvantages of processing:

Table 3-6 Advantage and disadvantages of RAP processing options (West, 2010)

Process	Possible Advantages	Possible Disadvantages
Use of milling without further processing	• Avoids further crushing of aggregate particles in RAP, which may allow higher RAP contents in mixes • Lowest cost of RAP processing options • Millings from large projects are likely to have a consistent gradation and asphalt content	• Requires multiple RAP stockpiles at the plant • Millings from individual projects are different; and therefore, when a particular millings' stockpile is depleted, a new mix design must be developed with another RAP.
Screening RAP before crushing	• Limits crushing of aggregate particles in RAP, which reduces dust generation	• Few RAP crushing and screening units are set up to pre-screen RAP
Crushing all RAP into a single size	• Allows the processed RAP to be used in many different mix types • Generally, provides good uniformity from RAP materials obtained from multiple sources • Large RAP stockpiles can be generated for annual production	• Tends to increase the dust content of RAP stockpiles, which may limit how much RAP can be used in mix design
Fractionating RAP	• Using different sized RAP stockpiles provides greater flexibility in developing mix designs	• Requires the most space for multiple smaller stockpiles • Most expensive processing option (cost of fractionation unit plus additional RAP cold feed bin) • May generate an excess of a RAP size if the mix designs are not balanced to the RAP feed

3.6.3 Handling/stockpiling

Any RAP material produced and not used in the same road is transported to a central stockpiling location for future use. The RAP materials can be collected from different road pavements and sent to stockpiles. In such cases, care must be taken to avoid contamination and segregation as well as mixing materials with different characteristics. It will be important to record details of each load as it arrives to the stockpiling site and make sure that the height of the stockpiling is not more than 3 m (Gerardu, 1985). On the other hand, RAP from different sources stockpiled on one site may have an advantage with the process of crushing and screening which will help in balancing the variation in RAP materials (West, 2010).

A survey conducted in 2015 in the USA (NAPA, 2021) shows that the total estimated amount of RAP stockpiled reached 85.1 million tons. The same study indicated that 74.2 million tons of RAP material was used in asphalt mixes in the year 2015 in the USA. Earlier studies also show that in the USA over 90 million tons of asphalt pavement material were reclaimed in the early 1990s (Copland, 2011).

The production of RAP material is the highest in the developed countries, as seen from studies (EAPA, 2017; NAPA, 2017); while no data could be found during this study that shows the amount of recycled pavement materials in African countries. Although some studies show there are pavement recycling works in South Africa (Mhlongo, et al., 2014; Alemayehu & Andrew, 2015; Ware, 2006).

Unless in-place recycling methods such as FDR and cold in-place recycling is not used, the milled asphalt pavement is transported and stockpiled at a central location for further processing and use in a central plant mix. Poor management of the reclaimed asphalt pavement in a stockpile result in contamination and loss of this valuable material. It is also considered as one of the deterring factors not to use RAP materials in large percentages in asphalt mixtures (West, 2009).

Management of RAP materials in a stockpile should be given more attention, and RAP from single or multiple sources need to be managed properly. When RAP materials from multiple sources are to be stockpiled, it may be necessary to crush the material to get a suitable size for use in asphalt mixtures and also to improve the consistency of the resulting RAP (Copland,

2011). It is necessary to decide, based on the specification requirement, whether to stockpile RAP materials from multiple sources in one pile or to put each RAP from different sources into different piles. According to the study by (West, 2009) in the USA, the decision of putting RAP materials from different sources in a single pile or not is dependent on the following factors:

- Whether the state or primary local agency allows RAP from other sources in asphalt mixes produced for its agency specifications;
- Whether or not the state or other primary local agency requires captive stockpiles or allows continuous replenishment of stockpiles;
- Whether or not an incoming material is likely to have contaminants;
- The space available at the plant site for RAP processing and stockpiling;
- The target RAP percentages in the asphalt mixes to be produced; and
- How much RAP comes from a single project.

The requirements from local agencies or limitations from specifications need to be adhered to for the use of RAP materials in larger percentages in bituminous mixtures. It may also be possible to blend RAP materials from different sources after processing (crushing and screening). Care should be taken during the processing of the RAP materials to avoid contamination and strong quality control procedures must be in place.

The moisture content of RAP materials in a stockpile needs to be kept to a minimum to avoid heating the RAP during asphalt mixture preparation. If possible, depending on the size of the pile, covering the material may be beneficial. Either using covering by an open-sided building or storing RAP on a paved and sloped surface can be useful to minimise the moisture in the stockpile (Copland, 2011). RAP materials in a stockpile should be:

- Free from foreign materials;
- Care should be taken to minimise the moisture content;
- Do not, if possible, use heavy machinery on stockpiles to avoid compaction;
- Stockpiles shall routinely be skimmed to break up lumps;
- Prevent or limit segregation;

- Preferably use an arc-shaped and uniformly layered stockpile.

Segregation of RAP material in stockpiling is a common problem. In large stockpiles larger particles tend to roll down and accumulate at the base of the stockpile and in such cases, it is better to use front end loaders to remix the material in the stockpile.

3.6.4 Composition and properties of RAP materials

Reclaimed asphalt pavement is a material composed of basically aggregates and bitumen obtained as a result of recycling hot mix asphalt (Al-Qadi, 2007). As the deteriorated asphalt pavement is milled by a milling machine or by an excavator from the surface of the road it is either in bitumen-bound loose material or in slab form. Apart from those resulting from the crushing of the aggregates in the process of milling and contamination from the underlying pavement layer, all the fine materials in the original mix stick in the RAP material. The laboratory separation of asphalt binder from the RAP will show the gradation and type of aggregate in Figure 3-7.



Figure 3-7 RAP materials from deteriorated pavement

3.7 Engineering properties of RAP materials

Engineering properties of RAP materials are considered to affect the performance of asphalt mix containing them. The quality of aggregates and bitumen in the RAP are of the main interest. The main engineering properties of RAP materials are, Gradation of aggregates, amount of asphalt cement in RAP, penetration, ductility and viscosity of asphalt cement.

Typical physical properties of RAP materials are summarized in the following table (FHWA, 2016)

Table 3-7 Physical and mechanical properties of RAP materials (FHWA, 2016)

Type of Property	RAP property	Typical Rang of Values
RAP Physical Properties	Unit weight	1940 – 2300 kg/m^3 (120 – 140 lb/ft^3)
	Moisture content	Normal: up to 5% Maximum: 7 – 8%
	Asphalt content	Normal: 4.5 – 6% Maximum Range: 3 – 7%
	Asphalt Penetration	Normal: 10 – 80 at 25ºC (77ºF)
	Absolute viscosity or Recovered Asphalt cement	Normal: 4000 – 25000 poises at 60ºC (140ºF)
Mechanical Properties	Compacted unit weight	1600 – 2000 kg/m^3 (100 – 125 lb/ft^3)
	California Bearing Ratio (CBR)	100% RAP: 20 – 25% 40% RAP and 60%Natural Aggregate: 150% or higher

3.7.1 Aggregates

3.8.1.1 Physical properties

i. Gradation

Aggregate particle size distribution is expressed as a percentage of the total sample weight. The process is that the sample aggregate is allowed to pass through a stack of standard sieves sizes in a decreasing size of openings from top to bottom. Particle size distribution test is carried out using the AASHTO T27 (ASTM C136) (Fwa, 2006) Particle size distribution of RAP material is one of the parameters required during the mix design process of asphalt mix containing RAP materials. It is a key factor in making decision during mix design and construction process (Nunn and Carswell, 2004).

A study by (Copland, 2011) show that there is a need to categorize aggregate sizes in to two as course fraction and fine fraction. This is known as Fractionation of the RAP aggregates and the course fraction is sizes over 9.5 or 12.5mm while the fine fraction is sizes lower than 9.5 or 12.5mm. The main purpose of fractionating RAP aggregates is believed to be improving the consistency of RAP; however, information gathered from US shows that there is no indication that fractionated RAP is better in consistency than unfractionated RAP.

Particle Size Distribution of RAP aggregate is dependent on the type and thickness of the existing pavement surface from which the RAP is obtained. Pavements which are overlaid at different times without removing the existing asphalt pavement may have variable aggregate sizes in different proportions in RAP obtained from such locations. According to Milton and Earland, 1999, nature and grading of RAP materials obtained through pulverization using recycling machines depend on the nature and thickness on the existing pavement to be recycled. It is, therefore, necessary to make considerations in using RAP materials especially from different stoke piles during mix design process and construction stage. According to the Wirtgen Cold Recycling Manual (Writgen, 2012) the grading of milled RAP material is influenced by various factors:

- The composition and uniformity of existing asphalt material
- The condition of the existing asphalt material
- The temperature of the asphalt in the milled horizon
- The depth of milling
- The speed of advance of the milling machine
- The rotation speed of the milling drum
- The type of milling drum and condition of the milling tools
- The direction of cut (up-cutting or down-cutting)

Determination of RAP aggregates particle size distribution is important to determine the necessary amount of virgin aggregate to be added to obtain the maximum density or strength of pavements constructed using recycling of existing pavement materials.

Due to mechanical degradation of aggregates during asphalt pavement material removal and processing the gradation is finer than virgin aggregates though the RAP aggregates can satisfy

the requirements of ASTM D692 and ASTM D1073 for coarse and fine aggregate requirements for bituminous pavement mixtures (FHWA, 2008).

In figure 3-7. gradation of recovered aggregate from RAP materials is shown. As can be seen from the graph majority of the test results are on the fine particle side and out of the gradation envelope of Asphalt Institute 1994. This justifies that the gradation of the RAP material will be affected by the milling and processing stage and becomes finer as expected. In the lower part the material fits in to the envelope which is below the 0.3mm sieve size. However, above the 0.3mm sieve size the RAP material starts to deviate from the envelope towards the finer side. More than 80% of the result shows that after 2.36mm sieve the particle size is outside the upper limit and are fine materials. The deviations are more pronounced on sieve sizes 2.36mm, 4.75mm, 9.5mm and 12.5mm. Thus, consideration is given to the gradation when using RAP materials and may be necessary to blend with virgin aggregates to correct the particle size distribution of the mix if used for surfacing.

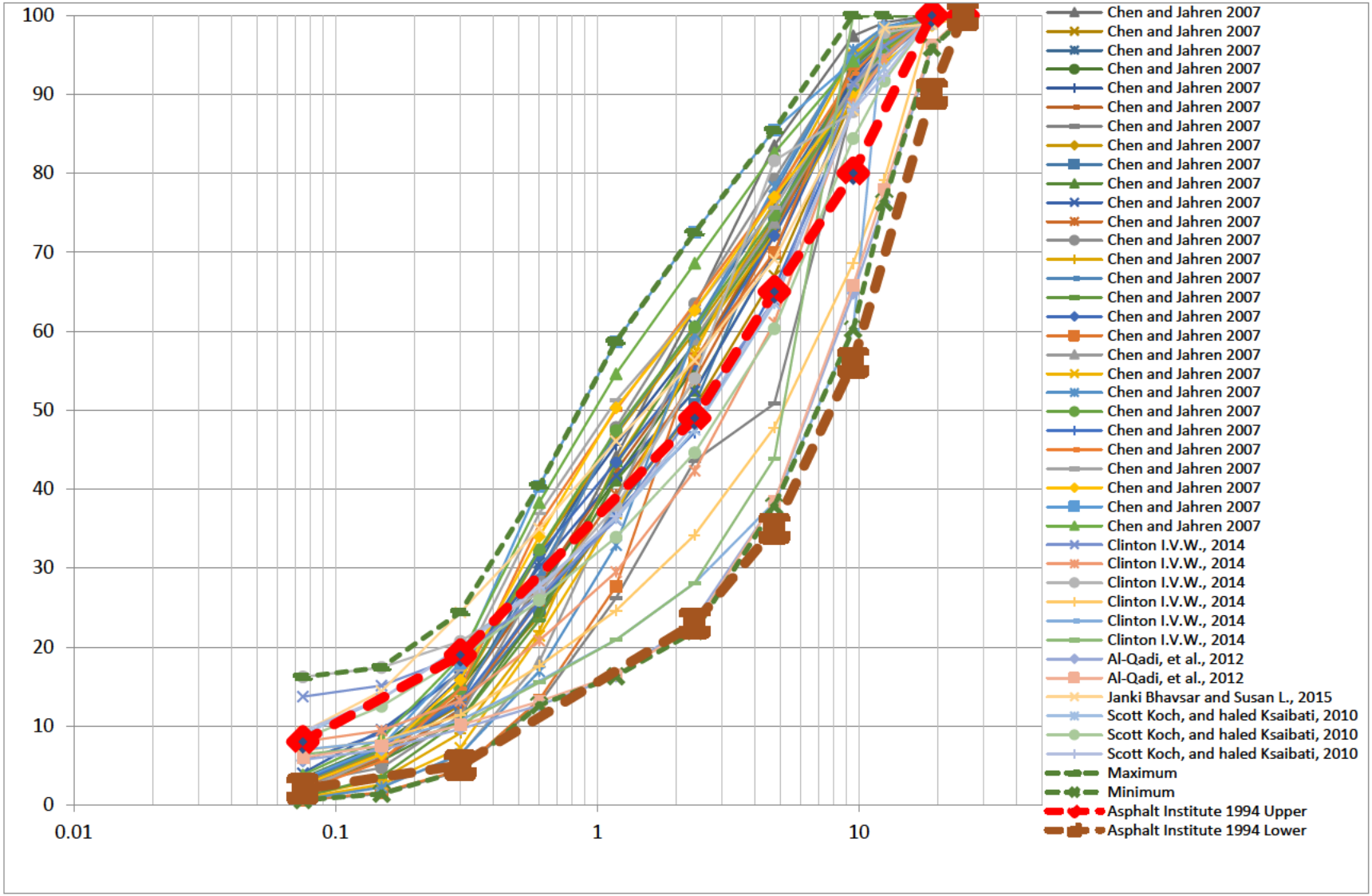


Figure 3-8 Particle size distribution of RAP aggregates (after binder extraction)

ii. Shape

The aggregate's shape is one of the physical properties that needs to be investigated. Most of the time during the milling and processing the shape of the original aggregate used in the hot mix may change. Flat, elongated, fractured surfaces and rounded shapes may be developed in the aggregate particles. Flat and elongated particles in the aggregate, also called flakiness, are an expression of the weight percentage of particles whose least dimension is 0.6 of the mean dimensions (Byrne, 2005).

The common tests that are conducted with respect to the shape of RAP aggregates are the coarse aggregate angularity (CAA) and fine aggregate angularity (FAA). The coarse aggregate angularity is measured as one of the shape factors measuring the degree of roughness and sharp angle of aggregate particles, and is determined manually by visual inspection (Han, 2011). In this method, the aggregates are visually inspected and the aggregates are separated into those with fractured faces and those without fractured faces (Thakur, 2012).

Fine aggregate angularity (FAA) also needs to be considered as the shape of finer particles may have an impact on the performance of the pavement. Rounded fine aggregates may lead to rutting and thus the test to investigate the FAA is carried out to ensure the aggregate has adequate angularity and texture to resist rutting (Han, 2011). This test can be conducted in accordance with the ASTM C1252 method (Thakur, 2012).

iii. Specific gravity

Specific gravity is a measure of the density of the aggregates as compared to the density of water at 23 °C (the specific gravity of water is assumed to be equal to 1 at this temperature). According to (West, 2014), the bulk specific gravity of aggregates is the most critical test for RAP materials, as it has an effect on the mixture's voids in mineral aggregate (VMA). The bulk specific gravity of RAP materials can be determined based on the following procedures (West, 2014).

1. Extract the binder either by the ignition method or by solvent method to separate the binder and aggregates.
2. Determine maximum theoretical specific gravity (G_{mm})of RAP (AASHTO T209).
3. Calculate effective specific gravity (G_{se}) of RAP using

$$G_{se(RAP)} = \frac{100 - P_{b(RAP)}}{\frac{100 - P_{b(RAP)}}{G_{mm(RAP)} G_b}}$$

4. Calculate bulk specific gravity (G_{sb}) as follows. Assume the percentage of the binder absorbed based on historic records.

$$G_{se(RAP)} = \frac{G_{se(RAP)}}{\frac{P_{ba} \text{ x } G_{se(RAP)}}{100 \text{ x } G_b} + 1}$$

The specific gravity of RAP aggregates can be determined using the AASHTO T85 for coarse aggregates and T84 for fine aggregates after the binder extraction, using either the ignition or solvent methods.

3.8.1.2 Mechanical properties

The mechanical properties of RAP aggregates are considered to be same as when they were used originally the first time. The properties depend on the original asphalt pavement type, the method(s) utilised to recover the material, and the degree of processing necessary to prepare the RAP for a particular application (FHWA, 2016). The mechanical properties are Los Angeles abrasion (LAA), aggregate impact value (AIV), aggregate crushing values (ACV), and ten percent fines value (TFV).

LAA - conducted to determine the abrasion and strength characteristics of aggregates. These properties of aggregates are important and are required so that the aggregate in the hot mix asphalt can withstand degradation, crushing and disintegration. It is assumed that the abrasion values of the aggregate obtained from Reclaimed Asphalt Pavement will not change and satisfy the requirements of specifications to be reused, as it was tested and allowed to be used the first time. According to the ASTM C131 and C535, the aggregate LAA value shall be less than 30 for the wearing course and less than 35 for the binder course (Ethiopian Roads Authority, 2013). If strong and hard igneous rocks are used the percentage loss due to the LAA test may not be more than 17% and for softer rocks such as gneiss the percentage loss could rise up to 57%.

ACV - a test designed to measure the crushing value of aggregates and is defined in TMH1 as "*The aggregate crushing value (ACV) of an aggregate is the mass of material, expressed as a percentage of the test sample. which is crushed finer than a 2.36 mm sieve when a sample of aggregate passing the 13.2 mm and retained on the 9.50 mm sieve is subjected to crushing under a gradually applied compressive load of 400 kN"*. The test is carried out either in wet or dry methods. In the dry method, the material is prepared and dried in an oven for 4 hours between 100 and 110 ºC and then tested. While in the wet method, after preparing the aggregate it will be soaked in water for 24 hours and surface dried and tested.

AIV - a relative measure of the resistance of an aggregate to sudden impact which is designed to measure the toughness of aggregate particles. The aggregate is subjected to successive blows from a falling hammer to simulate resistance to impact loading (Ethiopian Roads Authority, 2013). In this test aggregate is placed in a steel mould and subjected to 15 blows from a 13.5-kg weight dropped from a standard height (Byrne, 2005). As the name indicates, the test is about the sudden impact on the stone particles and is different from the slow impact or loading effect that results in a degradation of the stone particles. The AIV test on the RAP aggregates is similar to the procedures followed in testing virgin aggregates. This test is not suitable for soft rocks.

The 10% fines test can be used with all types of aggregates without consideration of their strength (Ethiopian Roads Authority, 2013). It can be used to determine the load that can produce 10 percent fines in the aggregates using the equipment used in the ACV test. It indicates the strength and brittleness of aggregates while it can also give indications on the packing density of aggregates.

3.7.2 RAP binder properties

According to the FHWA Report*,* **FHWA-RD-97-148,** the asphalt content of most old pavements will comprise approximately 3 to 7 percent by weight and 10 to 20 percent by volume of the pavement, and is more viscous and has lower penetration values as a result of ageing of the old pavement. The report also indicated that the penetration value may vary from 10 to 18 and absolute viscosity from 2000 to 50,000, depending on the time the existing pavement was in service.

Like the virgin binder, the extracted binder from an aged pavement (mixed with rejuvenator) is expected to fulfil the performance requirements such as rheology, adhesion and durability (Isacsson, 2006). Therefore, care must be taken in characterising extracted binder so that requirements are well identified in the preparation of mix designs. Binder extracted from RAP is characterised by decreased ductility and increased viscosity due to the ageing hardening effect. The need to improve these characteristics is important in the blending process with the virgin materials to get the desired mix characteristics required for good performance. According to (Al-Qadi et al., 2014), ageing of RAP binder occurs during construction and at the service life of the pavement. The mechanisms in which hardening occurs (Al-Qadi et al., 2014) are:

- Oxidation through diffusive reaction between the binder and oxygen in the air;
- Volatilisation through evaporation of the lighter components especially during construction;
- Polymerisation through chemical reaction of molecular components;
- Thixotropy due to the formation of a structure within the asphalt binder over a long period of time;
- Syneresis due to the exudation of thin oily components; and
- Separation through the removal of oily constituents, resins, and asphaltenes by absorptive aggregates.

One of the factors affecting the characteristics of aged binder is the level of moisture damage to the existing pavement (Al-Qadi et al., 2014); however, (Isacsson, 2006), argue that in fact, the recycled materials perform better with respect to moisture damage as the aggregates are already covered by a binder. They also indicated that softening aged binder using a low viscosity rejuvenator may be possible, however, it is difficult to obtain the two most important characteristics, stability and durability.

The amount and properties of bitumen in the RAP are determined in the laboratory after extraction, by either the solvent method or the ignition method of extraction. Extraction of the asphalt binder from the asphalt mix is mainly carried out to separate the binder from the aggregate to determine the binder content in the mix. Extraction of bitumen from the RAP can be done either by the ignition method AASHTO T 308 (ASTM D6307), or by the solvent method

AASHTO T164 (ASTM D2172) (West, 2010; Copland, 2011). In the ignition method, the mix is heated in an oven to burn the bitumen completely from the mixture and the binder content is obtained by determining the difference in the weight of the sample before and after burning. In the method of centrifuge or solvent removal, either trichloroethylene or another approved solvent is used to remove the asphalt binder from the aggregates.

Though solvent extraction and ignition oven are the most widely used methods, there are also other types of binder extracting methods used to separate the binder from aggregates, such as nuclear asphalt content gauge, pycnometer method, and automatic recordation method (Han et al., 2011). In the nuclear asphalt content gauge, a neutron source, such as Americium-241: Beryllium, is placed inside the gauge and the nuclear detector counts the number of hydrogen atoms in the asphalt binder. The number of hydrogen atoms present in the asphalt binder is proportional to the asphalt content. It is noticeable that water also contains hydrogen atoms and will affect nuclear asphalt content measurements. Since the nuclear asphalt content gauge does not separate asphalt the binder and the aggregate, it cannot be used to determine the properties of the aggregate.

Ductility is a measure of the cohesive strength of the asphalt binder. The test to determine the ductility is carried out at a low temperature in a water bath and the bitumen is stretched until it ruptures (Whiteoak, 2003). Asphalt binder extracted from the RAP material will not have the quality of virgin binder due to ageing occurring over time. When asphalt binder ages, one of the qualities lost in the process in is its ductility; it decreases and the binder becomes stronger and brittle. One of the purposes of rejuvenating agents in recycling of aged pavements should be to improve the ductility and increase the binding ability of the aged asphalt binder.

With respect to the penetration and viscosity of extracted binder, a study indicated that these two properties did not show significant differences compared to virgin binder (Kandhal, 1997). Blending of binder extracted from RAP and virgin binder requires an understanding of the remaining characteristics of the extracted binder so that a decision is reached as to how much virgin binder is added.

3.8 RAP durability

The durability of RAP materials is characterised by their resistance to moisture and temperature sensitivity during the service life of the pavement. (El-Hamrawey et al., 2015) defined the durability of bituminous mixtures as the resistance to the continuous and damaging effect of water. Pavements constructed using recycled materials alone or in combination with virgin materials are expected to sufficiently withstand the effects or damages due to moisture and temperature, and especially those associated with low temperature. Durability is also affected by damages on the existing pavement such as stripping. Some studies claim that pavements showing the stripping problem should not be recycled as the problem may re-occur in pavements constructed with RAP containing them, while others argue that they can be recycled by using anti-stripping agents (Robert, 2006). Therefore, durability of recycled asphalt pavements is said to be achieved if the pavement does not show these defects for a reasonable time as specified during the design period.

The major types of damages which show the measure of durability of recycled pavements are rutting development and cracking on the surface. The cracking and bearing capacity of the pavement can be described as the resilience-related response of the pavement and rutting as a permanent response (Robert, 2006).

Performance of pavements made from recycled materials may not significantly differ as long as the design and construction process are followed correctly. A study by (Kandhal, 1997), also shows that based on performance tests conducted on a number of virgin and recycled pavements in the state of Georgia in the USA, no statistically significant differences are found. (Kilpatrick, 2009) also discussed that recycled asphalt compared to the conventional asphalt of the same type does not behave much differently, as long as the material components and composition and the construction methods are not different.

Use of RAP materials in the manufacturing of hot mix asphalt has advantages associated with durability. In the study by (El-Hamrawey et al., 2015), it is indicated that apart from minimising the environmental impact and energy consumption, RAP improves durability and results in good stripping resistance of the hot mix asphalt containing RAP materials. The durability of recycled asphalt can be improved through stabilisation with various stabilising agents. The most common

stabiliser is cement, and it is used in many recycling projects to increase the strength of the mix. Some studies however, indicate that cement if applied in larger quantities will have a drawback due to its contribution to cracking of the mix. (Brown, 2009), suggests the cement content to be 1% for RAP content between 50 to 75%, indicating that lower cement content will not be sufficient to stabilise the material while higher cement content may cause cracking. (Jang et al., 2015) examined the durability of Reclaimed Asphalt Pavement using cementless binders and polymers and found that the result showed that outstanding durability can be achieved.

3.9 Environmental impact

Roads are one of the major causes of environmental degradation in locations where they are constructed. Their construction also affects or changes the topographical features in some cases as it involves deep cuts, removal of vegetation and production and processing of natural construction materials such as crushed stones and natural aggregates. This impact continues throughout the life of the roads as maintenance and rehabilitation requires production and transporting of virgin materials. Environmental impact is now one of the key issues being watched by all relevant stakeholders and minimising the impact is believed to be key to combatting the prevailing climate changes that are affecting many sub-Saharan African countries.

(Levis, 2011) indicated that recycling of asphalt pavements significantly reduces the GHG emissions and other emissions that affect the environment by reducing the global warming potential (GWP). In flexible pavements, the production of asphalt binder incurs the greatest environmental impact out of all the raw materials in the material production stage (Young, 2014). The use of recycling for pavements is environmentally important as the amount of virgin binder to be used decreases significantly and as a result, leaves a decreased impact on the environment.

The production of aggregates has a significant impact on the environment as it affects the ecological characteristics and consumes a lot of energy, which in effect produces a lot of greenhouse gasses (GHG). Recycling also reduces the impact as aggregates can be recycled over and over again. (EAPA, 2014) indicates that aggregates are unlikely to be affected by ageing and reprocessing for reuse, and if they have been satisfactorily used previously, they can perform

similarly in a recycled asphalt pavement. This is very important as reduction in extraction of new or virgin aggregates means a significant benefit in reducing environmental impact.

With respect to the type of recycling method, cold in-place recycling which reduces the tracking of materials and saves energy from the lack of necessity to heat the materials, has a minimised environmental effect. The amount of harmful GHG is reduced compared to the traditional methods, and thus provides less of a contribution to global warming. It shall also be noted that in the case of using stabilisers, such as cement in the process of rehabilitation, it will decrease the benefit of cold in-place recycling, as the production process of cement is highly energy consuming and it uses an extensive amount of natural resources which also produces GHG (Turk, 2016). In terms of contribution to global warming, both the traditional method and cold in-place recycling (using cement as a stabiliser) have almost similar effects.

In developing countries, incorporation of RAP in the pavement rehabilitation design procedures and guidelines may have benefit in utilising the asphalt waste generated in rehabilitation and reconstruction of road pavements. The contribution towards minimising the adverse environmental impact is much higher, as the landfill waste is reduced and also the GHG emissions from production and transportation of virgin aggregates. A study by (Lee, 2010). indicated that recycled asphalt used in the base and sub-base can reduce the effect of global warming by about 20% and minimal changes in the design of pavements to incorporate recycled asphalt can limit the greenhouse gas emission at its current level (Lee, 2010).

In road construction and rehabilitation, the pavement part is the main producer of GHG compared to the other aspects such as earthwork, structures, culverts, and road furniture. Furthermore, the contributors to high GHG emissions from pavement construction are from material production, transportation and machinery (World Bank, 2010). This is further strengthened from the result of a study by (Lee, 2010), in which it is stated that in construction of pavements the major reduction in GHG emissions is from material production and indicating that about 74% reduction in the CO_{2e} is obtained.

Table 3-8 Greenhouse gas emission by work item (World Bank, 2010)

Emissions (t CO_2 eq./km)	Expressway	National Road	Provincial Road	Rural Road - Gravel	Rural Road - DBST
Earthworks	161.4	15.89	12.00	2.74	2.68
Pavement	1333.86	424.66	157.3	72.20	85.53
Culverts	238.48	51.45	16.69	11.85	11.57
Structures	1067.99	119.39	20.57	3.03	2.95
Road Furniture	432.40	182.42	0.00	0.00	0.00
Total	**3234.12**	**793.81**	**206.56**	**89.82**	**102.74**

As can be seen from Table 3.9 pavements do contribute more compared to the other components of the road construction works. In expressway construction the contribution of the pavement accounts for 41% of the total CO_{2e} per km; while for the rural gravel road it is 80%; and for the rural road with DBST surfacing it is 83%.

This indicates that the material production is the highest contributor to GHG emissions, indicating the recycling of asphalt pavements is environmentally feasible and contributes to the reduction of GHG emissions significantly from the road construction and the rehabilitation.

3.10 Benefit of recycling

Asphalt pavement recycling has numerous advantages, as described in many of the literature works reviewed. In the literature review and background sections, the possible advantages and limitations of each recycling method are presented in detail. Therefore, here, in order to avoid duplication, the details are left out and the major benefits that are repeatedly indicated in almost all the literature selected for analysis are presented. All the literature included in the systematic review have indicated these benefits either as whole or individually, based on the type of recycling method they were addressing. Therefore, it can be concluded that recycling our deteriorated pavements is beneficial in the following aspects:

- cost effective,
- environmentally friendly,
- energy saving,
- conservation of natural resources.

These are the common benefits across all recycling methods compared to the traditional method of rehabilitation. When addressing the benefits of recycling of asphalt pavements, it is worth

repeating here that even if recycling may not be cost effective, it should be considered as it has potentially intangible benefits such as conservation of natural resources, energy conservation and preservation of the environment (Shoenberger, 1992).

Regarding benefits of asphalt pavement recycling in the context of developing countries, sufficient information could not be obtained in the selected literature. However, after the study of the benefits of asphalt pavement recycling it can be concluded that all the benefits equally relevant to the developing countries. It is even better to embark on recycling of existing asphalt pavements in order to conserve limited natural resources, save on the ever-increasing energy demand and protection of environment.

Table 3.1 shows that most of the studies analysed in this research indicated the benefits that can be obtained from recycling of asphalt pavements.

3.10.1 Benefit/cost of RAP

Use of RAP materials in different layers of pavement can be considered as a cost saving practice due to the fact that the recycled aggregates eliminate the mining, processing and transportation of virgin aggregates. Depending on the percentage of RAP material used in the new mix the cost saving varies; however, it can be argued that as %RAP is increased the saving in cost will increase (Ksaibati, 2015). The other perspective is that savings can be obtained from transporting and damping of removed asphalt pavements from damaged road pavements to landfill locations.

The cost/benefit analysis of Reclaimed Asphalt Pavement is evaluated based on the cost of production and processing of RAP materials and the anticipated performance of the pavement layer made out of RAP or material mixed with RAP. As indicated above, the other benefits can be taken as added benefits to the use of RAP, which ultimately makes the RAP materials beneficial to mainly the road sector.

Economic analysis of using RAP materials can be carried out using different techniques. Currently there are six main economic analysis techniques widely used (Kandhal, 1997; ARRA, 2001; Wirtgen, 2012) as shown below:

- Present Worth of Cost (PWoC)
- Benefit/Cost (B/C)

- Internal Rate of Return (IRR), and
- Net Present Value (NPV)
- The Equivalent Uniform Annual Cost Method
- The Cost-effective Method

The techniques can be broadly categorised into two based on the underlying principle of analysis (Wirtgen, 2012). In the first category, the cost of each alternative is calculated and the result is compared. In the second category, both the cost and benefit of each alternative are calculated; PWoC and B/C fall under the first and second category respectively.

Depending on the type of recycling method used and the specific project conditions, the level of saving may vary. The cost saving from cold in-place recycling may be higher than hot recycling methods compared with the traditional rehabilitation method. The percentage of reclaimed asphalt pavement materials used in a mix also has impact on the amount of saving obtained. Few studies indicated that as the percentage of RAP added increased, the saving also increased, as shown in Figure3.9. The saving obtained will encourage agencies to use more RAP and reduce land fill associated problems.

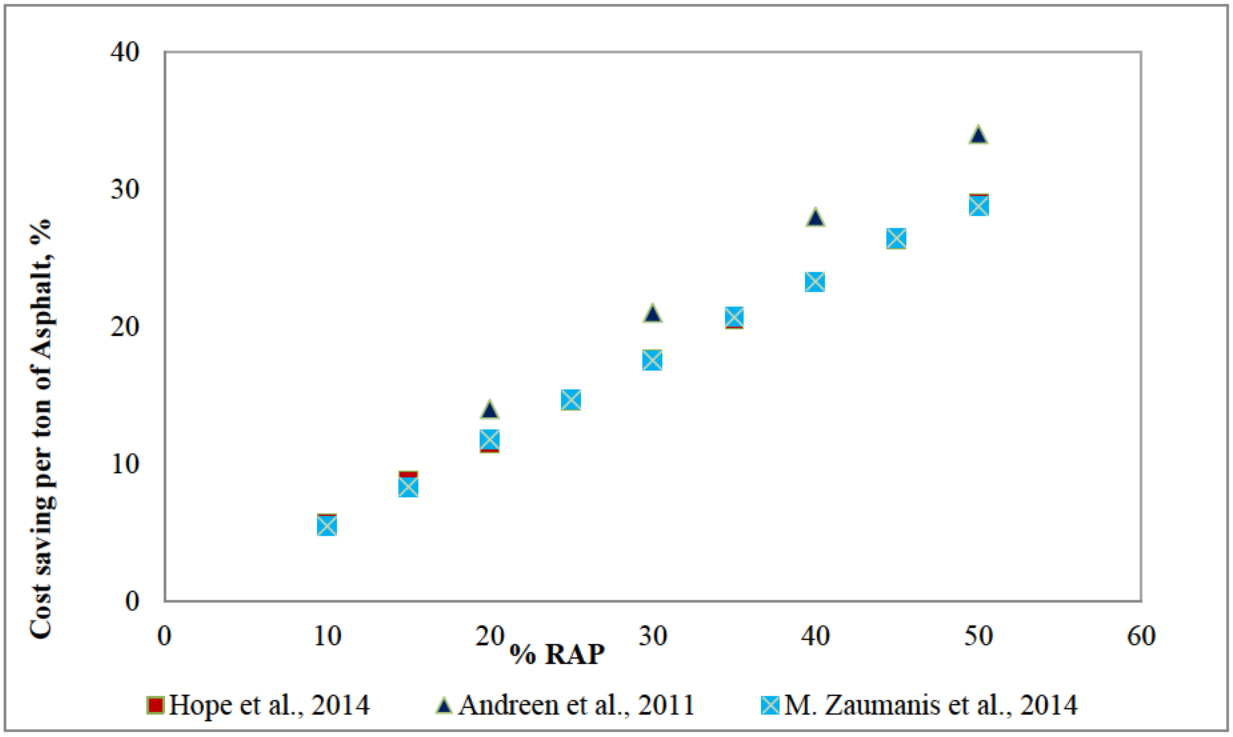


Figure 3-9 Potential cost saving from using RAP

3.10.2 Cost of recycling

Cost components of recycling are mostly the capital cost and operation cost and revenues. The capital cost components are the equipment capital and working capital; operating cost incorporates overhead costs, equipment operation and maintenance, supplies, fuel, permits and labour; while the revenue consists of average product price and tipping fees (fee paid for the dumping or land fill).

According to Wilburn, recycling requires initial capital expenditures of approximately $4 per ton of production capacity for a large recycling operation, to about $8 per ton for a small operation. In general, larger operations are not as capital intensive as smaller operations. Where the supply of recycled material from a road is small, this may be an indication that it may not be advantageous to establish a recycling operation, as it may not justify the capital cost required. Economic performance of the recycling operation is also impacted by the objective and technology of the recycling choice (Horvath, 2004).

Cost/benefit calculation

(Morian, 2016), suggested a simple benefit/cost calculation for evaluation of pavement recycling methods as follows:

$$\frac{Benefit}{Cost} = \frac{EAC\ of\ Recycling\ technique}{EAC\ of\ virgin\ mix}$$

Where EAC = Equivalent Annual Cost = $\frac{Total\ Initial\ cost\ (\frac{\$}{ton})}{Expected\ perfromance\ life\ in\ years}$

Based on the result of analysis carried out to evaluate the cost benefit, Dennis and Luis concluded that the recycling techniques used are more economical than all mixes of the conventional method (hot mix asphalt). Furthermore, an increased amount of RAP materials in the mix decreases the relative cost of the mix.

Using RAP materials in the rehabilitation works benefits road agencies due to the minimised use of virgin materials. A study by (Horvath, 2003), compared the savings from different percentages of RAP material used and the result also showed that as the percentage of RAP increased, the saving increases, indicating the benefit of using RAP materials.

A report by (SHATEC Engineering Consultants, 2013), demonstrated a cost benefit obtained from cold in-place recycling by comparing it with a conventional rehabilitation method, which showed a 23% saving was obtained. It is evident that cold in-place recycling can give cost savings, which is a benefit on top of other benefits, such as less environmental impact, and less energy requirement as a result of less extraction and transportation of virgin aggregates.

3.11 Application of RAP

Reclaimed Asphalt Pavement can be used for the purpose of pavement maintenance, rehabilitation, and reconstruction (ARRA, 2001). The type of recycling method is selected based on detailed information from the field regarding the condition of the pavement; the defect types, their extent and severity; and other relevant information useful for decision making in the selection process. According to (ARRA, 2001), hot in-place recycling can be used in the maintenance of pavements as a preventive action, which is intended to maintain the durability or flexibility of the pavement; while hot in-place, cold in-place and full depth reclamation can be used in the rehabilitation of pavements. When the road is highly deteriorated and the existing structure is not adequate to carry the traffic or if there is a requirement for the realignment of the geometry, cold central plant recycling, full depth reclamation and hot recycling can be used as a reconstruction solution.

The use of the recycling type with respect to the condition of the pavement was suggested by (NCHRP, 2011), as the indicative guideline to show the type of recycling versus the condition of the pavement. Full depth reclamation is better used if the pavement is deteriorated to the level of a poor rating; while hot-in place recycling can be recommended as a preventive maintenance action when the pavement is still in good condition.

Reclaimed Asphalt Pavement materials can be used in different layers of the pavement structure during rehabilitation or reconstruction. In the 1950s and 60s use of recycled hot mix asphalt diversified into using it in the base course (Johnson, 1992). Furthermore, reclaimed asphalt pavement (RAP) can be used as a granular base or sub-base material in virtually all pavement types, including paved and unpaved roadways, parking areas, bicycle paths, gravel road rehabilitation, shoulders, residential driveways, trench backfill, engineered fill, pipe bedding, and culvert backfill (FHWA, 2016).

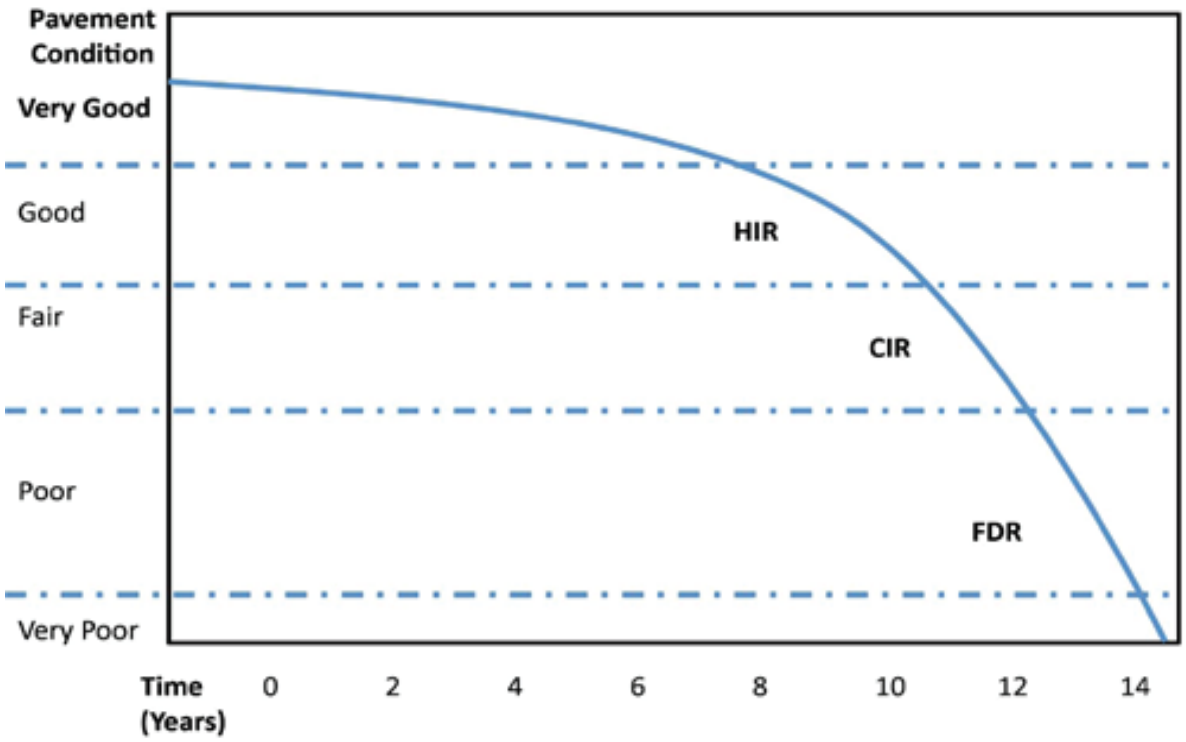


Figure 3-10 Pavement condition and types of recycling (NCHRP, 2011)

A number of studies have been conducted to evaluate the use of RAP materials in a base course (Brown, 2009; Blankenagel, 2005; Taha, 2002; Chomicz-Kowalska, 2013; Saride, 2015). RAP materials are commonly used as the surfacing course in asphalt pavements. In the hot plant recycling method, the existing pavement is mixed with a proportion of virgin aggregates and binders to use it as a surfacing mix. Proper characterisation of the RAP is carried out for both the extracted aggregates and the binder to determine the amount of virgin materials in the mix.

Some studies have shown that there is an advantage in using recycled materials in lower pavement layers. (Wilburn, 1998) indicated the advantages and disadvantages of using recycled concrete products for a sub base aggregate as follows:

i. Advantages

- Recycled concrete is non expansive and will not grow or expand with moisture.
- Recycled concrete has an optimum moisture of approximately 13 percent - about twice that of natural road base, due to its particle size distribution. It may absorb twice the water before becoming saturated.

- Recycled concrete is 10–15 percent lighter in weight, resulting in reduced transportation costs.
- Recycled concrete compacts faster - up to two to three times as fast as a non-stabilised natural road base.

ii. Disadvantages

- They are often composed of material with highly variable properties.
- Their strength values are often lower than those of natural aggregates, resulting in product application limitations.
- Use of recycled material must be evaluated on a project-by-project basis in order to determine suitability. Customers are often not used to matching material characteristics with project quality requirements.

The selection and application of a specific type of recycling method depends on many variables that need to be evaluated. The level of distress of the pavement, the available technology, the expected economic benefit, and environmental issues are examples of these variables. (Kandhal, 1997) discussed in detail the applicability and consideration of different recycling methods in the following table.

Table 3-9 Applicability of recycling methods (Kandhal, 1997)

Process	**Applicability**	**Considerations**
1. Hot Mix Recycling	Can be used to treat surface defects; deformation; loaded and non-loaded associated cracks; and maintenance patching. Material obtained from an existing pavement can be stockpiled for future use. Also, stockpiled RAP material can be carefully blended in a plant with other materials to achieve a proper mix.	Percentage of RAP that can be used depends on recycling mix properties and the type of hot mix plant. RAP/virgin material blend is typically 10:90 to 30:70, with a maximum of 50:50 (drum plant).

2. Hot In-place Recycling	Can be used to treat surface defects; corrugation and surface rutting; and longitudinal and slippage cracking up to 50 mm (2 in) depth. The existing pavement material can be used fully, resulting in a minimal demand for virgin materials. Hence, substantial savings in transportation costs can be realised. This method can reduce rehabilitation time significantly, and is particularly suitable for busy highways or streets which cannot be kept closed for a long time.	Hot in-place recycling can involve significant amounts of heavy machinery and equipment. Because of high mobilisation costs, there should be enough work in a particular area (either for a single project or for a number of projects) to make this process cost effective. Also, since this method frequently involves long equipment trains, it may not be suitable for local residential streets with very limited space for manoeuvring of equipment. This process can produce air quality problems, for pavements with a significant number of patches made with liquid bituminous materials and/or crack sealing material.
3. Cold In-place Recycling	Can be used to treat rutting in asphalt layers below the surface; load-associated block and thermal cracks; and maintenance patching. The existing pavement material can be used fully, and therefore, substantial savings can be achieved by avoiding transportation of new materials. Also, since no heat is used in this technique, there are no air quality concerns associated with	In most cases cold in-place recycled materials require a curing period, followed by an application of a wearing course. Although smaller machines are available, this technique can involve long trains which may not be suitable for local residential streets with very limited space for manoeuvring of equipment.

	it, and savings are also realised in energy and money. This method can improve the structural capacity of an existing pavement. Also, disturbance to traffic is limited and can be used for busy highways which cannot be kept closed for a long time.	
4. Full Depth Reclamation (FDR)	Can be used to treat rutting in layers below the surface, including base; also, for load associated, block and thermal cracking; and maintenance patching. This technique is particularly suitable for pavements with base problems or insufficient structural capacity. Since this is basically a cold in-place process, it has all the advantages of cold in-place recycling, including savings in transportation costs and energy and no occurrence of air quality problems due to emissions. Different manufacturers have large single machines which can complete this process in a single pass.	Full depth reclamation usually results in a new base, which must be covered with an appropriate wearing course. As in cold in-place recycling, a significant amount of curing period may be required. At present, there is a lack of proper construction guidelines and specifications for FDR, and the whole process must be supervised by an experienced person. Since in this method a part of the non-asphalt layer is also recycled, the resulting mix must be carefully monitored for any contamination by undesirable material (such as vegetation or large chunks of RAP).

Application of the asphalt pavement recycling methods can also be dictated by the type of defects on the surface of the deteriorated pavement. According to the Asphalt Recycling and Reclamation Association (ARRA, 2001), an in-depth condition survey of the pavement shall be

conducted to fully understand the types and extents of defects in the pavement. Inadequate information about the condition of the pavement may lead to improper selection and use of recycling methods. The following table is proposed by ARRA for selection of the recycling methods:

Table 3-10 Guide for selection of pavement rehabilitation based on defect types (ARRA, 2001)

Type of Pavement Distress	Cold Planing	Hot Recycling	Hot In-place Recycling	Cold In-place Recycling	Full Depth Reclamation
Surface Defects					
• *Ravelling*	X	X	X		
• *Bleeding*	X	X	X		
• *Slipperiness*	X	X	X		
Deformation					
• *Corrugation*	X	X	X		
• *Rutting-Shallow*	X	X	X		
• *Rutting – Deep*		X		X	X
Crack/Load Associated					
• *Alligator*		X		X	X
• *Longitudinal-Wheel path*		X	X	X	X
• *Pavement edge*		X		X	X
• *Slippage*		X	X		
Crack/Non-load Associated					
• *Block (shrinkage)*		X		X	X
• *Longitudinal – Joint*		X	X		
• *Transverse – Thermal*		X		X	X
Reflection		X		X	X
Maintenance Patching					
• *Spray*		X		X	X
• *Skin*		X		X	X
• *Pothole*		X		X	X
• *Deep (hot mix)*		X		X	X
Problem Base/Subgrade (soft, wet)					X

3.12 Recycling technology/machines

Recently, the type of equipment and methods of asphalt pavement recycling have evolved and various technologies are now available for use with increased efficiency. In the study by (Horvath, 2004), the recycling type and required equipment are indicated (to be used in PaLATE, a life-cycle analysis tool). This indicates which type of recycling machines are required for the particular recycling method to be applied. It can also give an indication for planning purposes when rehabilitation projects are to be implemented. It should also be noted that the selection of equipment type depends on the rehabilitation type on a project-by-project basis.

Table 3-11 Equipment types required for recycling

Activity type	**Equipment**
Cold In-place Recycling	CIR Recycler
	Pneumatic Roller
	Tandem Roller
Full Depth Reclamation	Asphalt Road Reclaimer
	Vibratory Soil Compactor
Hot In-place Recycling	Heating Machine
	Asphalt Remixer
	Pneumatic Roller
	Tandem Roller
Rubblization	Multi Head Breaker
	Vibratory Soil Compactor
Milling	Milling Machine
Concrete Demolition	Multi Head Breaker
	Wheel Loader
HMA Production	Asphalt Mixer

3.12.1 Asphalt pavement milling machines

The Asphalt Recycling and Reclaiming Association has defined five classes of cold milling (Kandhal, 1997):

- Class I - milling to remove surface irregularities
- Class II - milling to uniform depth as shown on plans and specifications
- Class III - milling to a uniform depth and cross slope as shown on plans or special provision
- Class IV - milling the entire depth to the base or sub grade
- Class V - milling to variable depths at different locations as shown on the plan and specifications

Over the years asphalt pavement recycling machines have evolved into very efficient and versatile machines. They are modified from milling machines and basic soil stabilisers to specialized recyclers (Wirtgen, 2012). They have also become very large and powerful machines that can recycle thick pavements in a single pass. They have environmentally friendly engines which produce fewer emissions through intelligent emission control mechanisms and low noise emissions. The recycling machines vary from tractor-towed recyclers to heavy duty trains of machines that can recycle pavements in one go.

3.12.2 Cold planing/milling machines

According to ARRA, the minimum equipment required for cold planing is that it should be a modern and self-propelled recycler, or haul truck, water truck and sweeper or broom. Cold planing equipment is available in a variety of sizes from high-capacity machines capable of milling up to 4.9 metres wide and a depth over 300 mm in one pass, to mini-milling machines used for localised milling around manholes and valves (ARRA, 2001).



Figure 3-11 Road milling machines and type of milling drum (Kahndal and Mallick, 1997)

Over time the design of milling teeth has improved significantly and helped in lowering the cost of cold planing/milling. The current machines are fitted with tungsten carbide tools on the cutting drum, which is very strong and durable (ARRA, 2001). The sizes of the machines vary in width and depth of milling. Modern machines can now mill the full width of the pavement carriageway and up to a depth of 380 mm at a time (Kandhal, 1997). Since the RAP has been generated from the milling process and is removed from the site, self-loading milling machines are available in all sizes. Front loading milling machines are now the standard in the industry as they save time and money, since the only lane to be closed to traffic is the lane being milled (ARRA, 2001).

3.12.3 Cold recycling machines

Cold recycling of pavements is simple in terms of the concept. The machines used in the recycling job, however, have a complicated process that is very important for successful operation and obtaining good results. Cutting, mixing and compacting the materials in a consistent manner is important to obtain uniformity in the material matrix, which is in turn very important for the performance of the pavement structure. For in-place recycling work a specially designed powerful machine is needed, that has a drum with strong cutting bits installed for cutting and pulverisation of the existing distressed pavement (Wirtgen, 2012).

According to (Brock, 2006), the extremely high volumes of traffic today make road repairs much more difficult than in the past. The public demands minimal interruptions, and the milling and inlay process greatly reduces the time needed. The coupling of the process of rehabilitation is then of paramount importance for reducing interruption of the movement of traffic during the construction work. The full process is carried out by a train of equipment put into the sequence for the rehabilitation procedure, such as cutting, additive mixing and pulverization, paving and compacting. The following general set-up (Figure 3-12) is used in the in-place recycling (Brock, 2006). However, it is to be noted that the configuration of the set-up may change based on the type of recycling machine, type of work and place of work (urban or rural).

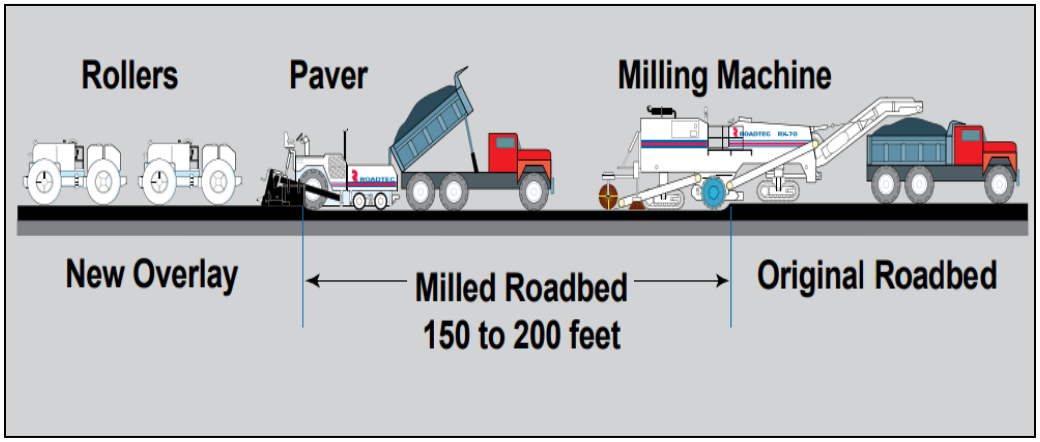


Figure 3-12 General set-up of equipment for in-place recycling (Brock and Richmond, 2006)

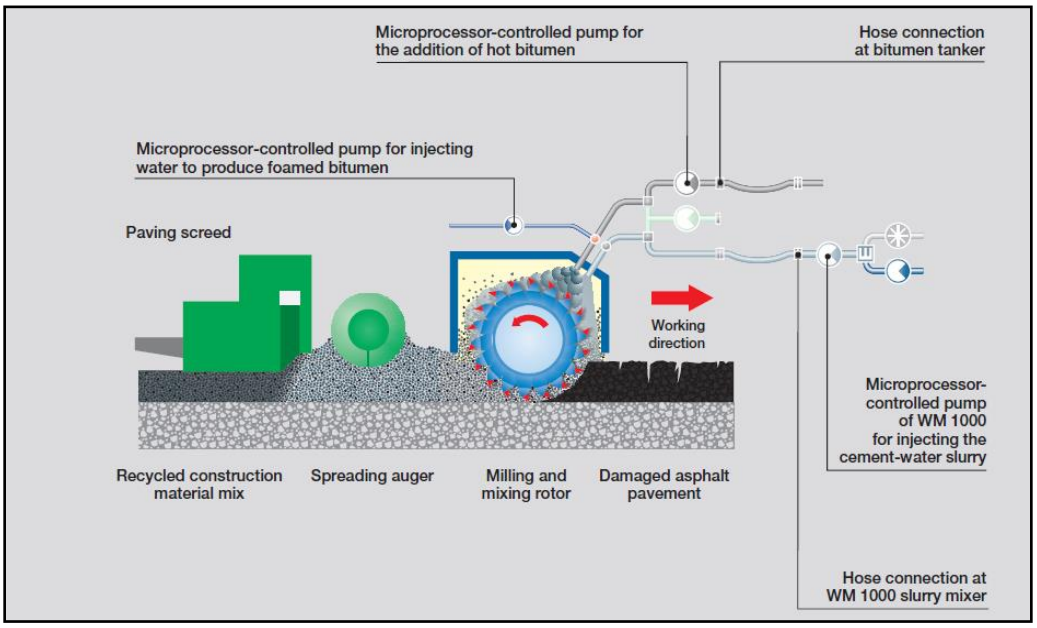


Figure 3-13 Process of cold in-place recycling (Wirtgen, 2012)

In cold in-place recycling, the recycling machine cuts the pavement, granulates, mixes the injected binding agents and water in the machine's heavy-duty milling and mixing chamber to create a homogeneous new mix. The process of cutting and remixing with or without additives takes place in one go in the recycling machine. This process allows for a fast-working time and produces a uniform mix. The process in the machine is illustrated in the figure below (Wirtgen, 2012).

Cold recycling machines can be divided into two types: tyre mounted or truck mounted. Tyre mounted recyclers are mainly designed for recycling and they come in several models, sizes and capacities. These machines are used in pulverising thick layers of bound pavement materials up to 500 mm thick (with larger machines). In the tyre mounted recyclers, the cutting points are arranged in a chevron pattern which helps the cutting and mixing of the pavement in a vertical axis only. With truck mounted recyclers the cutting teeth are arranged in a helical pattern that enables movement of the material both in the horizontal and vertical axis and helps to windrow the material to the centre of the cutting drum (Wirtgen, 2012).

3.12.4 Full depth recycling machines

The FDR operation can be carried out using normal road construction equipment such as a motor grader and roller compactors in conjunction with a self-propelled reclaiming machine (ARRA, 2001). For more complex projects the following additional construction equipment may be required:

- end or bottom dump haul trucks
- windrow sizer or calibrated aggregate spreader
- water truck complete with spray bar
- calibrated bulk spreader for dry stabilising agents
- mixer and tankers for slurry application of stabilising agents
- asphalt emulsion tanker(s) and distributor truck
- computerised liquid or foamed asphalt additive system on the reclaimer
- front end loader

The full depth recycling operation can be carried out in different ways varying from a multi-step to a single-step process (Kandhal, 1997). In the multi-step operation, the removal, crushing, mixing with additives, and compacting of the reclaimed material is carried out in a standalone operation. The cutting can be carried out using a dozer or motor grader with ripper, with various equipment size reduction and pulverization follows. However, currently there are a variety of technologies that can combine all the different operations into a single step. The single pass recycling machine is set up in such a way that the operation of cutting, mixing with additives and laying of reclaimed material is finished in a single machine with attachments to water and other additives in a feed tanker.

Cold in-place recycling and the FDR process have similar applications and the machines used and set-up is similar. In FDR the depth of cutting is extended to incorporate the underlying base layer. The following figures show the full depth recycling operation and set-up of the machines (Wirtgen, 2012).

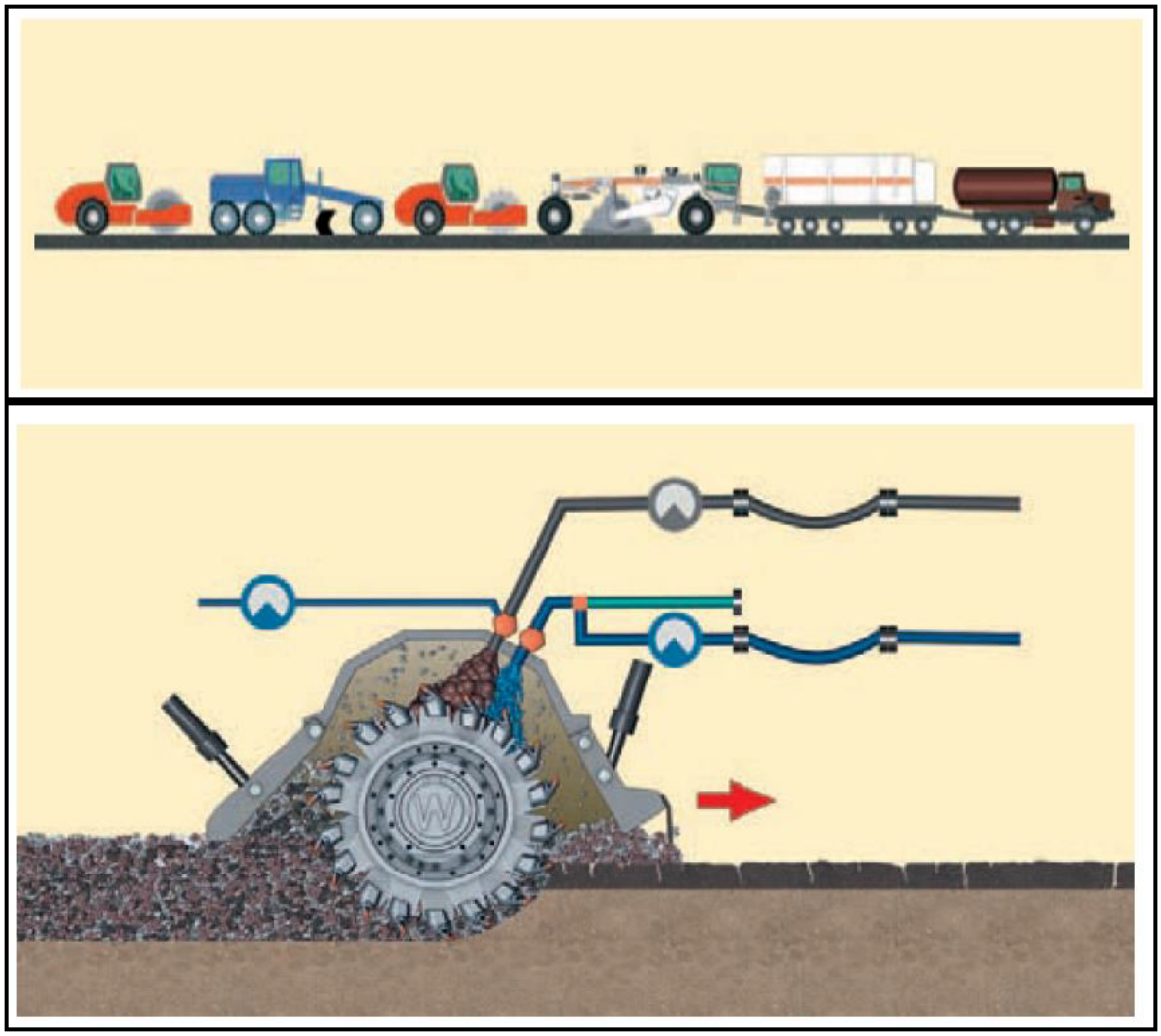


Figure 3-14 Full depth reclamation process

3.12.5 Hot in-place recycling machines

This is an onsite or in-place recycling method and requires heating of the pavement surface before recycling. Hot in-place asphalt pavement recycling is less common compared to the cold in-place recycling as it requires more energy for the heating of the pavement. Hot in-place recycling involves the following activities (FHWA, 2016):

i. Pre-heating to soften the pavement surface by propane radiant, in which the surfacing is milled, remixed with or without a heater; the surface is scarified to a predetermined depth; rejuvenator added; then remixing, paving and compacting. The compaction follows the traditional compacting method.

ii. Repaving, which is a more sophisticated process, involves heating and scarifying the existing pavement surface to a depth from 25 to 50 mm and adding and mixing in a rejuvenating agent to improve the asphalt's viscosity. The recycled material is placed as a levelling course using a primary screed, and simultaneously a thin hot mix asphalt overlay up to 50 mm is put down. Conventional equipment and procedures are used immediately behind the train to compact both layers of material to ensure a monolithic bond between the new and recycled layer.

iii. The remixing process is carried out when the addition of new material is required to improve the strength or stability of the recycled asphalt concrete. Scarified or milled RAP is blended with rejuvenator and new virgin aggregate or new hot mix asphalt, and secured by a compacting screed. Conventional equipment and procedures are used to place and compact the remixed material.

Hot in-place recycling can be carried out in a single pass operation or a multiple pass operation, where, in the former case, all the heating, scarifying and mixing with new material and rejuvenators, paving and compacting is carried out in one pass. A multiple pass is when a new wearing course is required after re-compacting the RAP material. The technology used in the hot in-place recycling is shown schematically in Figure 3-15 (Kandhal, 1997).

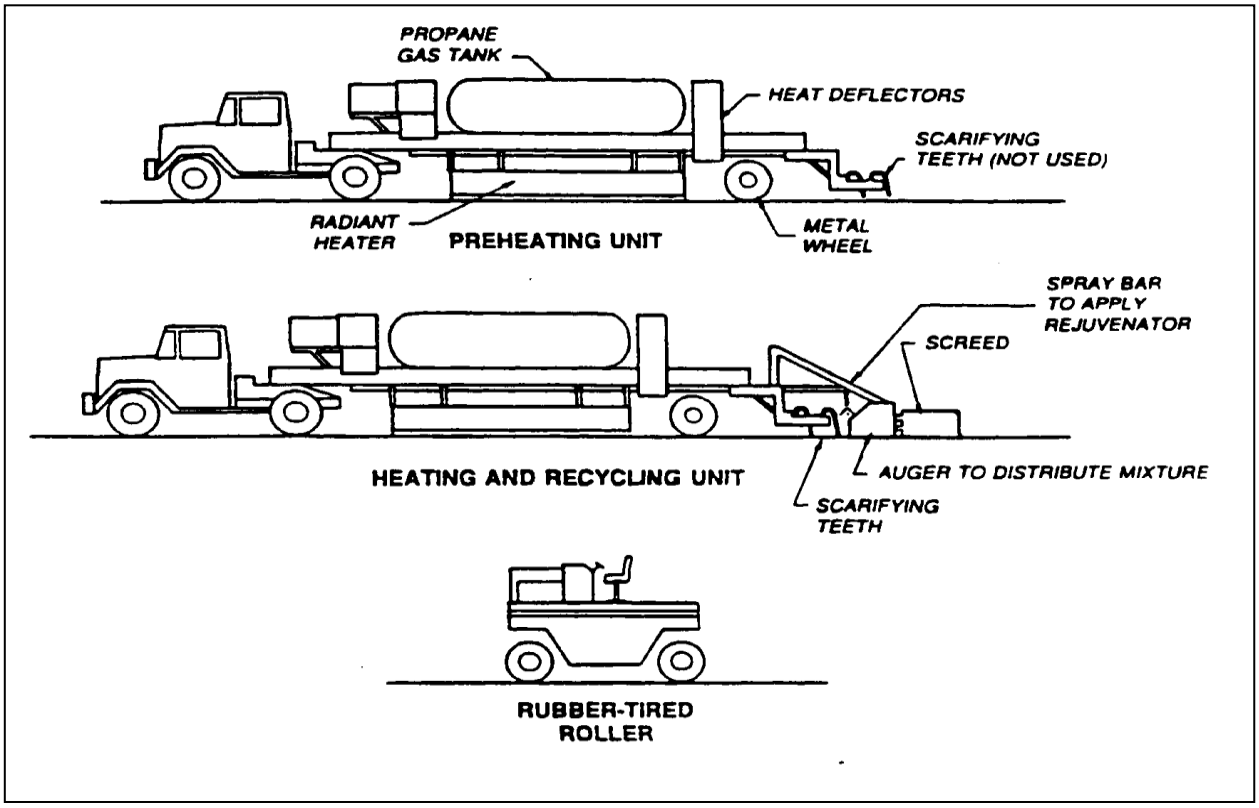


Figure 3-15 Hot in-place recycling process set-up (Kandhal, 1997)

3.13 Policy and practice background

During the initial stages of the Ethiopian Road Sector Development Program (RSDP), between 1997 and 2002 the A1 trunk road has been recycled and used as a base course. In the later stage a 65-km segment on the A3 trunk road has been rehabilitated using foamed bitumen technology. These are the only recycling efforts that can be mentioned in the Ethiopian roads sector in terms of the existing practice regarding asphalt pavement recycling.

So far there is no policy framework for the implementation of asphalt pavement recycling. Thus, one of the aims in this study is to develop a policy framework that is required for the successful implementation of asphalt pavement recycling technology in Ethiopia. Recycling is not well practiced in Ethiopia due to various reasons. The concept that natural construction material is abundantly available is overshadowing the fact that natural resources are non-renewable and their uncontrolled use may affect the needs of the future generation. The other most important factor is the lack of clear policy that supports the use of recycling in the construction sector, including road construction and maintenance.

The availability of a policy framework has many advantages, as they guide and force construction waste generators to properly dispose of their wastes into recycling plants or other appropriate disposal schemes. Due to a lack of such a policy framework, in Ethiopia, construction and demolition wastes from road rehabilitation are disposed of inappropriately, impacting the environment, the social well-being around and in the construction location. In some places the construction waste is disposed of within the construction area or left onsite. To encourage recycling of asphalt pavement or construction and demolition a waste policy framework shall be put in place. The policy can be in three forms: *i, direct regulation; ii, market incentives; and; iii, education* (Cochran, 2006).

Direct regulations require or encourage waste diversion by the generators. Disposal bans, percentage and material recycling requirements, green building requirements, recycling goals, and salvage requirements are all examples of direct regulation. Market incentives make waste diversion more appealing by making it a more economical option. Disposal taxes, subsidised recycling, business development, and advance disposal fees/deposits/rebates are examples of market incentives. Education policies spread information to the public to make them aware of recycling opportunities (Cochran, 2006).

4 DEVELOPING AN ASPHALT PAVEMENT RECYCLING SELECTION METHOD

4.1 Introduction

In selecting the most appropriate asphalt pavement recycling method, evaluation of each recycling method based on the well-defined suitability/appropriateness criteria or measures is important. In this study these criteria are developed considering the current environmental, economic and social aspects. The recycling methods are required to satisfy the selection criteria as an appropriate method that can be implemented in Ethiopia. The criteria themselves are first evaluated to check if they are appropriate and important for evaluating the recycling methods. Then, they are used to evaluate each recycling method through a rating system that aims to weigh the advantages and disadvantages of the recycling methods on a scale from 1 to 4 (1 being highly advantageous, while 4 is disadvantageous and not suitable to be used).

Accordingly, the suitability criteria/measures are first developed and are defined below as the definitions of the criteria/measures to be used in the context of this study only. The following suitability/appropriateness measures were selected based on expert views and recommendations in Ethiopia. The words “suitability” and “appropriateness” were used interchangeably for this study. To evaluate each of the available asphalt pavement recycling methods these suitability measures are used and they are defined as follows.

4.2 Defining selection criteria

4.2.1 Ease of construction

Some technologies are very complicated and require highly skilled labour and sophisticated machinery. In such cases, for developing countries, it will be difficult to transfer technologies and use them in a sustainable manner. Therefore, care must be taken during selection and transferring of certain technologies so that frustrations are avoided during the implementation stage. Accordingly, it will be very important to select an asphalt pavement recycling method that is suitable for the current road sector in terms of construction and use of available skill, with very minimal training, and with awareness during the implementation stage. It should also be a method that requires less supervision with simplified procedures for the construction process. Thus, ease of construction is one

of the suitability measures in evaluating the available asphalt pavement recycling methods.

4.2.2 Cost effectiveness

One of the benefits of asphalt pavement recycling is to save the cost of rehabilitation and maintenance, since it reduces the use of virgin aggregates (production, processing and haulage) in the asphalt mix it will mean savings in cost. For example, if 50% of the aggregate volume in the mix is from reclaimed material the saving will be significant. In some rare cases if 100% of reclaimed material is reused in the rehabilitation process the benefits are much more attractive. The cost saving is not only from the direct substitution of the input materials, but also from the associated labour and equipment utilisation in the preparation and transportation of new materials to the site.

Use of specialised construction equipment also has significant implications on the cost of using specific technology. The operation and maintenance of such specialised equipment puts an unnecessary burden on the process of transferring the technology and on the sustainability of it. Therefore, it is important that the recycling methods are evaluated using cost effectiveness as one of the suitability criteria.

4.2.3 Environmental sustainability

Roads are one of the major causes of environmental degradation in locations where they are constructed. They affect or change the topographical features in some cases, as deep cuts, removal of vegetation and production and processing of natural construction materials such as crushed stones and natural aggregates are all involved. This impact continues throughout the life of the roads as maintenance and rehabilitation requires production and transporting of virgin materials. Thus, the recycling technology shall be evaluated based on its impact on the environment.

Environmental impact is now one of the key issues being considered by all the stakeholders and minimising the impact is key to combatting the prevailing climate changes and global warming. Thus, any selected specific asphalt pavement recycling

method shall have minimal impact on the environment and environmental sustainability is used as one of the suitability measures to evaluate the recycling methods.

4.2.4 Economic sustainability

Economic sustainability is defined as the delivery of overall economic benefits in terms of less frequent maintenance, less quantity of virgin materials (both bitumen and crushed stone), and utilisation of less energy (from processing and transportation). The distinction between "cost effectiveness" and "economic sustainability" is that the latter refers to benefits obtained in life-cycle terms from using a specific recycling method.

4.2.5 Energy saving

Construction of roads involves a lot of energy consumption during material production, processing and transportation. This is due to the need to employ a variety of equipment, some heavy, in the process with high energy requirements. In asphalt surfacing projects (both AC and chip seals) heating of bitumen and aggregates needs a lot of energy. Thus, replacement of virgin materials with recycled materials would help to reduce the energy required for the production, processing, transportation and final construction. However, it must also be noted that the recycling process itself has an energy consumption that is significant and must be estimated and compared with the energy requirement for the production, processing and transporting of virgin materials.

4.2.6 Suitable for labour intensive work

Although recycling of asphalt pavements requires heavy machinery, some aspects may be suitable for employing semi-skilled labour. Highly automated systems may require little or no unskilled labour. However, in developing countries with a large population, utilising the work force may be of paramount importance. From the viewpoint of sustainability, instead of using these machines due to their technical nature and operation costs, the recycling method that has options of a semi-automated nature or that can employ semi-skilled labour could be beneficial. Therefore, recycling technology that can be customised to be labour intensive or involving labour in the process will be more preferable than fully automated systems of asphalt pavement recycling.

4.2.7 Minimised use of virgin materials

One of the main advantages of recycling is preserving the ever-dwindling natural resources, such as virgin aggregates and other road construction materials, through reusing the existing pavement materials in the construction and rehabilitation of pavements. Although all recycling methods are aimed at different targets of reusing recycled materials, those types of recycling with a higher percentage of reusing Reclaimed Asphalt Pavement materials are preferable. Thus, recycling methods that can accommodate a higher percentage of RAP materials were more preferable.

4.2.8 Suitability for small-scale contractor

In developing countries, such as Ethiopia, the involvement of small-scale contractors in the road sector is considered to be advantageous in the process of developing local skill and financial capacity. Therefore, asphalt pavement recycling methods that utilise less complicated equipment and systems that can easily be implemented by small-scale contractors are beneficial to the Ethiopian condition and is considered as one of the suitability measures in the selection of the most appropriate recycling method.

4.2.9 Suitable for low-volume roads

Asphalt pavement recycling methods that are suitable for rehabilitation of low-volume roads are highly preferable as there is a significant length of such roads and also due to their frequent need for maintenance and rehabilitation compared with AC pavements. The use of Reclaimed Asphalt Pavement materials in the construction of low-volume roads' surfacing can be an advantage and hence it is considered in the evaluation of the recycling methods.

4.2.10 Suitable for different climatic conditions

As Ethiopia has regionally variable weather conditions, with a hot climate up to a maximum of 40 to 50 ºC, cold areas down to 0 ºC in the highlands, and in the south and south west parts of the country there are high rainfall areas where precipitation can be greater than 1500 mm, a recycling technology that can be applied in all areas of the country irrespective of such climatic variation is highly desired. could be a big advantage and this is taken as one of the suitability criteria in the selection of the most appropriate asphalt pavement recycling methods.

4.3 Evaluation of selection criteria using an analytical hierarchy process (AHP)

A matrix of the alternatives to be compared was prepared and values of judgments (referred to as vector judgement values) were assigned based on the experience of experts who were asked to fill in the matrix. The experts who participated in filling in the matrix are six PhD students at the University of Birmingham and eleven engineers from the Ethiopian Roads Authority. Each expert evaluated the importance of one criterion over another based on the scale given in Table 4-1. Then the average value was taken to derive a single reciprocal matrix as defined by Saaty (1990).

Matrix A = (a_{ij}) where $\mathbf{aij} = \frac{\mathbf{wi}}{\mathbf{wj}}$,

i, j = 1 … n has positive entries everywhere and satisfies the reciprocal property, $\mathbf{aji} = \frac{\mathbf{1}}{\mathbf{aij}}$

Any Matrix with this property is called a reciprocal matrix. In addition, A is consistent because the following condition is satisfied:

$$\boldsymbol{a} \cong \frac{\boldsymbol{aik}}{\boldsymbol{aij}} \qquad \text{where i, j, k = 1…n}$$

Table 4-1 Scale of judgment for pairwise comparison (Saaty, 1990)

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the adjacent judgments	When compromise is needed
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.	
Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

The matrix analysis resulted in the Importance Factor for each of the suitability criteria are shown in Table 4-2 below

Averages of vector judgment values together with consistency measures and were then determined, and finally importance factors are determined. A final check for consistency (C) was conducted and the value obtained was $C = 0.089 < 0.1$, which indicates the analysis was consistent. Once the importance factors are established, they are later used in the evaluation of the suitability of recycling technologies that can be applied in the local conditions of Ethiopia.

Table 4-2 Importance factor of criteria

Rank	Measure/Criteria	Importance Factor
1	Cost effectiveness	1.000
2	Ease of construction	0.892
3	Economic sustainability	0.683
4	Energy saving	0.523
5	Environmental sustainability	0.618
6	Minimised use of virgin materials	0.502
7	Suitable for labour intensive works	0.367
8	Suitable for low-volume sealed roads	0.313
9	Suitability for small-scale contractors	0.315
10	Suitable for different climatic conditions	0.303

Based on the pair-wise comparison, *"Cost effectiveness"* was the highest ranking indicating that it has the highest priority/importance compared to the other criteria. The second highest priority is *"Ease of Construction"*. As can be seen from Table 4-2, "*Suitability for small-scale contractors*" and "*Suitability for different climatic conditions*" have the lowest score.

The structure of hierarchy is formulated for the developed criteria and recycling types and presented in Figure 4-1. The goal is to select the appropriate pavement recycling method based on the criteria.

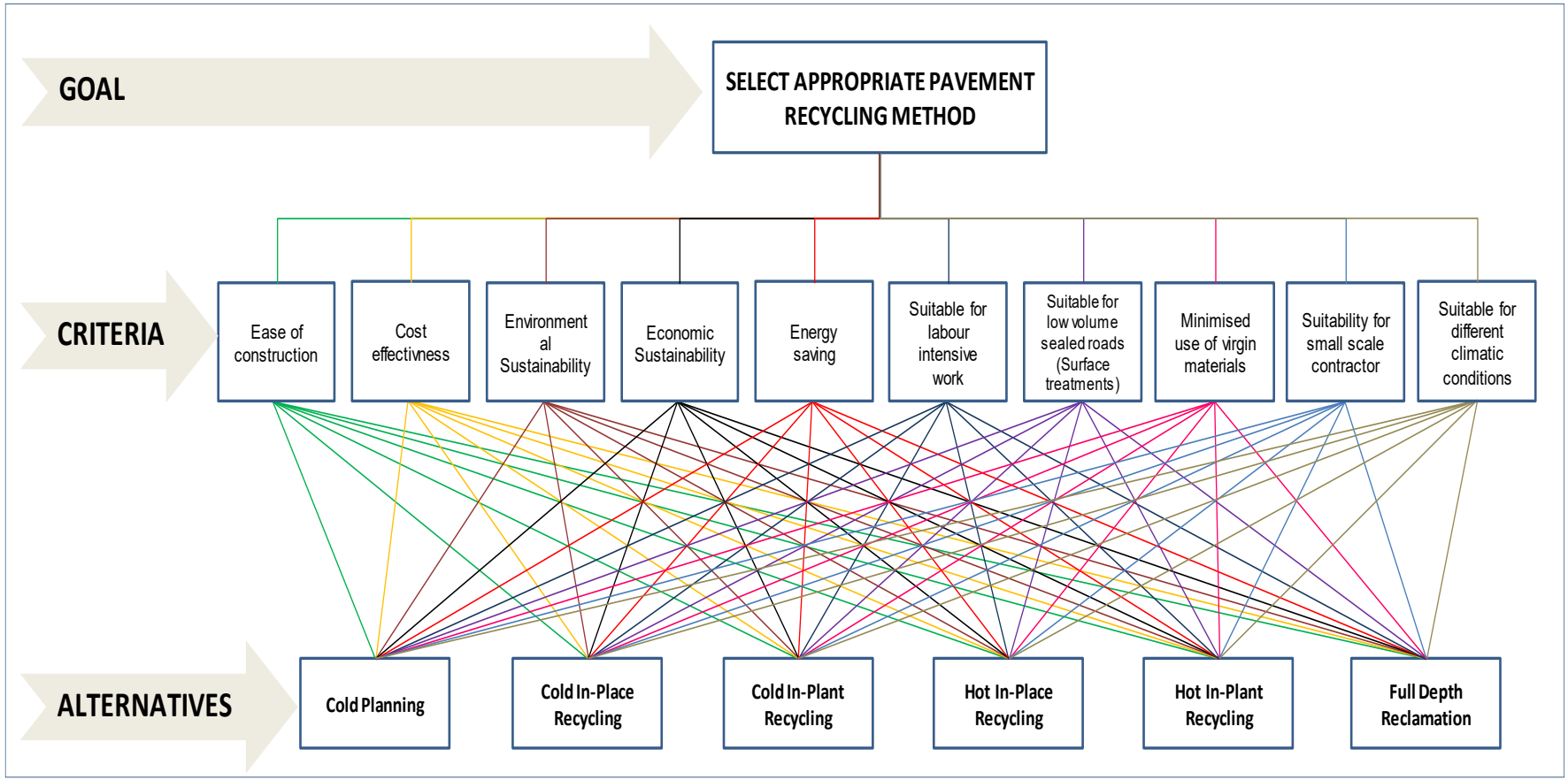


Figure 4-1 Structure of hierarchy

4.4 Results

The analytical hierarchy process method described in the previous section has been used to generate a matrix for the evaluation of selection criteria. Pair-wise ranking is carried out to evaluate each of the suitability criteria with each other and their preference over the others.

Table 4-3 Pairwise comparison matrix

	Suitability Measures	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Sum**
1	Ease of construction	1.0	1.8	1.7	2.0	2.0	3.0	1.3	2.8	1.5	1.3	**18.4**
2	Cost effectiveness	0.55	1.00	2.73	1.75	2.69	3.17	2.66	2.92	2.81	2.7	**23.0**
3	Environmental Sustainability	0.60	0.37	1.00	1.69	1.50	1.92	1.54	2.18	1.75	1.8	**14.4**
4	Economic sustainability	0.49	0.57	0.59	1.00	2.11	2.92	2.28	2.83	1.80	2.2	**16.8**
5	Energy saving	0.50	0.37	0.67	0.47	1.00	2.38	1.43	2.21	2.34	1.9	**13.3**
6	Suitable for labour intensive work	0.34	0.32	0.52	0.34	0.42	1.00	1.73	1.47	1.65	1.3	**9.1**
7	Minimised use of virgin materials	0.75	0.38	0.65	0.44	0.70	0.58	1.00	3.65	2.41	2.1	**12.7**
8	Suitability for small-scale contractor	0.35	0.34	0.46	0.35	0.45	0.68	0.27	1.00	2.54	1.4	**7.8**
9	Suitable for low-volume sealed roads (surface treatments)	0.67	0.36	0.57	0.55	0.43	0.61	0.41	0.39	1.00	1.7	**6.7**
10	Suitable for different climatic conditions	0.75	0.38	0.55	0.46	0.53	0.78	0.47	0.72	0.59	1	**6.2**
	Total	**6.01**	**5.88**	**9.40**	**9.11**	**11.83**	**16.98**	**13.13**	**20.21**	**18.39**	**17.36**	

The vector judgment values are filled by the voters or experts in such a way that they fill the upper diagonal of the matrix and the lower diagonal is equal to the reciprocal of the upper diagonal. The next step is to normalise the matrix by dividing each entry in a column by the sum of the column to get the normalised value. The sum of each column after normalisation shall be one.

Table 4-4 Ranking suitability criteria

	Suitability Measures	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	Total score	Average	Consistency measure	Rank
1	Ease of construction	0.17	0.31	0.18	0.22	0.17	0.17	0.10	0.14	0.08	0.08	1.617	0.162	10.856	2
2	Cost effectiveness	0.09	0.17	0.29	0.19	0.23	0.19	0.20	0.14	0.15	0.15	1.813	0.181	10.895	1
3	Environmental sustainability	0.10	0.06	0.11	0.19	0.13	0.11	0.12	0.11	0.10	0.10	1.119	0.112	10.892	4
4	Economic sustainability	0.08	0.10	0.06	0.11	0.18	0.17	0.17	0.14	0.10	0.12	1.238	0.124	10.968	3
5	Energy saving	0.08	0.06	0.07	0.05	0.08	0.14	0.11	0.11	0.13	0.11	0.949	0.095	10.840	5
6	Suitable for labour intensive work	0.06	0.05	0.06	0.04	0.04	0.06	0.13	0.07	0.09	0.07	0.666	0.067	10.889	7
7	Minimised use of virgin materials	0.12	0.06	0.07	0.05	0.06	0.03	0.08	0.18	0.13	0.12	0.910	0.091	10.716	6
8	Suitability for small-scale contractor	0.06	0.06	0.05	0.04	0.04	0.04	0.02	0.05	0.14	0.08	0.571	0.057	10.593	8
9	Suitable for low-volume sealed roads (surface treatments)	0.11	0.06	0.06	0.06	0.04	0.04	0.03	0.02	0.05	0.10	0.568	0.057	10.494	9
10	Suitable for different climatic conditions	0.13	0.06	0.06	0.05	0.04	0.05	0.04	0.04	0.03	0.06	0.550	0.055	10.599	10
		1.00	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**		**Average**	**10.774**	
													CI	**0.086**	
													RI	**1.490**	
													C_Ratio	**0.058**	

To check whether the analysis made so far is consistent, the consistency ratio (CR) shall be determined. According to Saaty (1990), if the value for the CR is less than 0.1, the analysis is consistent and the result can be taken to rank the criteria. If the CR value is more than 0.1, the analysis shall be revaluated for its consistency. The consistency ratio CR is given by;

$$CR = CI/RI$$

Where, CR, is consistency ratio

CI, is the consistency index = $(\lambda_{max} - n) / (n - 1)$, where λ_{max} is the average of the consistency measure and *n* is number of criteria (n=10 in this case);

RI, is the random index = 1.49 (from AHP by Saaty, 1990);

Therefore: CI = (10.774-10)/(10-1) = 1.0774/9 = 0.086

CR = CI/RI = 0.086/1.49 = 0.058

CR = 0.058 < 0.1 so is ok.

Since the consistency ratio is < 0.1 the result of the analysis is consistent enough to be accepted, and based on this, the alternatives will be evaluated accordingly. Since the level of importance of each criterion is different, a factor is assigned to each criterion based on the total points each criterion scored in the matrix normalisation process. This "importance factor" is a numerical value assigned based on the ranking of the criteria. The highest rank was for "Cost effectiveness" and it will be used as a reference or as full point and the importance factor for others was calculated with respect to their "Total score" in Table 4-4. Thus, the factor of importance assigned for each of the criteria will be considered in the evaluation of the recycling alternatives. The selection criteria are evaluated and ranked, and the importance factor is assigned as shown in Table 4-5. In the pair-wise ranking process the "Environmental sustainability" criteria has scored the highest result and ranked first. Accordingly, the importance factor assigned to it will be 1.0. The importance factor of the others is then calculated based on the ranking in the pair-wise analysis result. The following table shows the importance factor of each of the selection criteria.

Table 4-5 Importance factors for suitability criteria

Rank	Measure / Criteria	Importance Factor
1	Cost effectiveness	1.000
2	Ease of construction	0.892
3	Economic sustainability	0.683
4	Energy saving	0.523
5	Environmental sustainability	0.618
6	Minimized use of virgin materials	0.502
7	Suitable for labour intensive works	0.367
8	Suitable for low-volume sealed roads	0.313
9	Suitability for small-scale contractor	0.315
10	Suitable for different climatic conditions	0.303

A questionnaire was developed to evaluate available asphalt pavement recycling methods that can be implemented in Ethiopia. It was aimed at local and international experts in the area of pavement and materials' engineering with a good understanding of asphalt pavement recycling technology. The questionnaire was based on the identified suitability measures and respondents were asked to evaluate each of the recycling technologies with respect to each criterion. The rating was based on a scale from 1 to 4, where 4 signified the highest advantage of the recycling technology with respect to the suitability measure/criteria and 1 showed no advantage.

Accordingly, 14 questionnaires were sent out to selected professionals from Ethiopia, the UK, South Africa, and Kenya. Twelve respondents filled and returned the questionnaire, i.e., 85%. Analysis of the responses received is discussed below. These professionals were carefully selected based on their experience in the developing countries, especially their intimate knowledge of the Ethiopian road sector.

Based on the response, the "cold in-place recycling" scored the highest average value of 2.38 (after being factored by the importance factor) on a scale of 1 to 4, and was considered the most suitable type of asphalt pavement recycling method. In second place was "full depth reclamation" with an average score of 1.97, and the "cold in-plant recycling" method was placed in third with a score of 1.95.

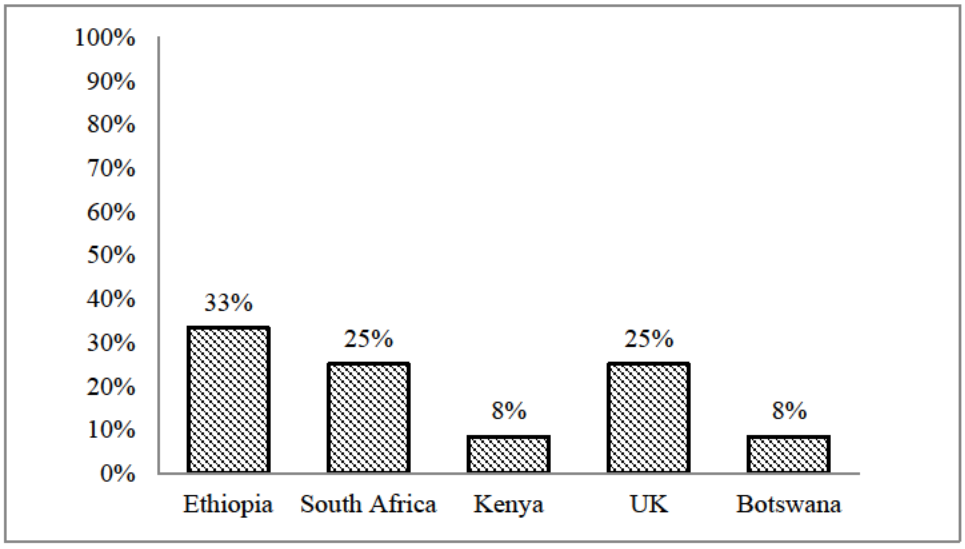


Figure 4-2 Respondents by country

Each type of the recycling technology was evaluated by the criteria and accordingly given a rank based on the result. Cold in-place recycling was ranked the highest while FDR and Cold in-plant were 2nd and 3rd respectively, as shown in Table 4-6.

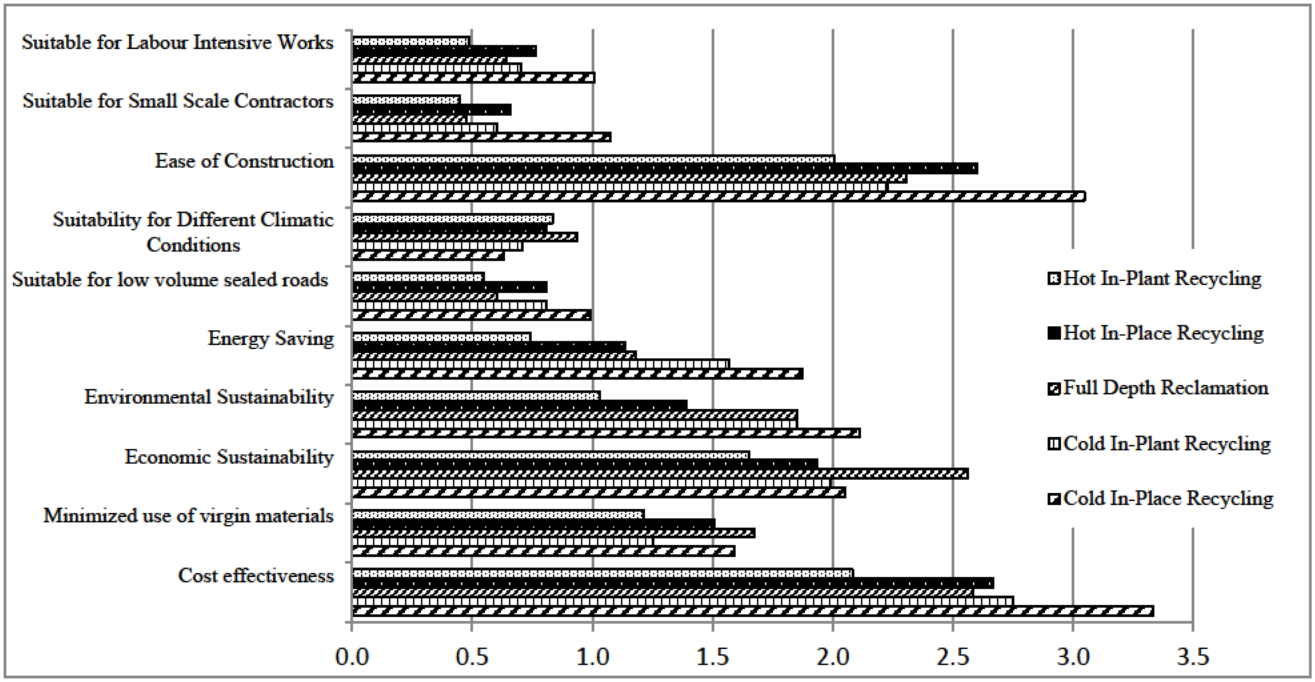


Figure 4-3 Frequency of respondents by each recycling type

Table 4-6. Ranking of recycling types based on the questionnaire responses

Recycling Type	Evaluation Points	Rank
Cold In-place Recycling	3.13	1
Full Depth Reclamation	2.58	2
Cold In-plant Recycling	2.54	3
Hot In-place Recycling	2.53	4
Cold Planing	2.33	5
Hot In-plant Recycling	1.95	6

The results of this selection exercise, based on the questionnaire analysis, are analogous to the systematic review and AHP. In both cases, cold in-place, cold in-plant and FDR were found to be the most desirable asphalt pavement rehabilitation methods. In both cases, cold in-place was the first choice, but FDR was the second choice in the questionnaire responses, while it was third

in the AHP. The general conclusion is that cold recycling was preferable to hot recycling in the case of Ethiopia, based on the rankings as shown in Table 4-6.

Table 4-6 Ranking of recycling methods by AHP result

	Cost effectiveness	Ease of construction	Environmental sustainability	Economic sustainability	Energy saving	Minimised use of virgin materials	Suitable for low-volume sealed roads	Suitability for different climatic conditions	Suitable for labour intensive works	Suitable for small-scale contractors	AVERAGE	RANK
Cold In-place Recycling	3.3	3.0	2.1	2.0	1.9	1.6	1.0	0.6	1.0	1.1	1.77	**1**
Full Depth Reclamation	2.6	2.3	1.9	2.6	1.2	1.7	0.6	0.9	0.6	0.5	1.48	**2**
Cold In-plant Recycling	2.8	2.2	1.9	2.0	1.6	1.3	0.8	0.7	0.7	0.6	1.45	**3**
Hot In-place Recycling	2.7	2.6	1.4	1.9	1.1	1.5	0.8	0.8	0.8	0.7	1.43	**4**
Cold Planing	2.2	2.2	1.5	1.4	1.3	1.2	0.7	0.8	0.7	0.9	1.27	**5**
Hot In-plant Recycling	2.1	2.0	1.0	1.7	0.7	1.2	0.5	0.8	0.5	0.4	1.10	**6**
Average	2.6	2.4	1.6	1.9	1.3	1.4	0.7	0.8	0.7	0.7		
Rank	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		

Based on the rankings of the criteria and recycling types, the following recycling type selection matrix is developed to simplify the selection process. Accordingly, categories are colour coded so that the most preferable and the less preferable can be easily visualised before going on to evaluate the criteria against the recycling types. The colour coding is given based on a scale of 3, based on the importance factor determined in section 4.4 and presented in Table 4-2. Accordingly, category 1 (Green) is allocated for the values greater or equal to 3. Those having values between 2 and 3 are given a scale 2 (yellow); while those below 1 have a scale of 3 (Red) as shown in Table 4-8.

Table 4-7 Color coding for recycling selection

Matrix category	Values in Table 5.20.	Colour code
1	>=3	Green
2	>=2 and <3	Yellow
3	<=2	Red

Table 4-8 Asphalt pavement recycling selection matrix

	Cost effectiveness	Ease of construction	Economic sustainability	Environmental sustainability	Minimised use of virgin materials	Energy saving	Suitable for low-volume sealed roads	Suitability for different climatic conditions	Suitable for labour intensive works	Suitable for Small-scale contractors
Cold In-place Recycling	1	1	1	1	2	2	3	3	3	3
Cold In-plant Recycling	1	1	1	2	2	2	3	3	3	3
Full Depth Reclamation	1	1	1	2	2	2	3	3	3	3
Hot In-place Recycling	1	1	2	2	2	2	3	3	3	3
Cold Planing	1	1	2	2	2	2	3	3	3	3
Hot In-plant Recycling	1	1	2	2	2	3	3	3	3	3

One can select the recycling type based on the specific requirements of the rehabilitation project by considering the criteria. For example, for projects that have a tight budget, strong environmental regulations and long-term economic benefits, one can select cold-in-place or cold-in-plant or full depth recycling methods. It is evident that asphalt pavement recycling is not suitable for labour intensive, low-scale contractors and is dependent on climatic conditions. From this analysis all recycling methods are cost effective and can easily be implemented.

The top three recycling types, cold in-plant, cold in-place and full depth reclamation are considered to be the most appropriate recycling types that can satisfy the top ranked criteria, as shown in the selection matrix (Table 4-8). Therefore, it can be concluded that asphalt pavement recycling is beneficial and can be implemented; while the selection of the types of recycling should be made following a structured approach as shown in this research work.

5 RESULTS AND ANALYSIS

5.1 Introduction

This study includes the following key components: a systematic review of the literature; an economic analysis of asphalt pavement recycling; a laboratory investigation on the performance of RAP materials; the development of the method for selecting recycling types; and the development of a policy framework for asphalt pavement recycling.

The systematic literature review showed that recycling asphalt pavement has a large economic benefit. Different recycling technologies are based on different approaches to the recycling problem suited to their methodology and application to the pavement structures, resulting in technology-specific cost savings. For example, full depth reclamation recycles the asphalt layer and some portion of the base course all together; hot in-place recycling is carried out on site by heating the distressed asphalt layer, reworking it and compacting; while hot in-plant recycling is carried out in an asphalt plant in a similar fashion to traditional hot mix asphalt (HMA) preparation. Therefore, comparing different types of recycling techniques in terms of economic benefit will be challenging and may lead to inconclusive results. However, it is possible to make an economic evaluation of recycling by considering the different layers of the pavement and different amounts of materials added in a new mix. Accordingly, in this research, the recycling of the asphalt layer of existing pavements was assessed in terms of factors described in chapter 4 section 4.2, by considering different amounts of RAP materials added to a new mix to be used in the asphalt road rehabilitation process.

Mixes containing RAP materials were also tested in the laboratory to assess their properties and hence, performance. The tests selected mainly focused on determining deformation and cracking parameters. The literature indicates that permanent deformation and cracking significantly contribute to the failure of asphalt pavement surfacing. Thus, investigating these factors would give a good indication of the performance of roads constructed using asphalt mixes containing RAP materials. The results of the laboratory investigation undertaken and their discussion are given in this chapter. Samples of existing pavement surface were collected from the south west of Ethiopia, from the Bedele – Metu Road section, which is part of a trunk

road A5-6 with high traffic volume. The samples were then prepared in the Road Research Centre (RRC) Laboratory of the Ethiopian Roads Administration.

The mix was designed in accordance with ERA 2013 pavement design guideline (Ethiopian Roads Authority, 2013) and percentages of RAP were substituted in the proportions indicated in Table 6.1. The Marshall mix design method was used to design the mixes. Indirect tensile strength (ITS), and rut depth measurement as performance tests were conducted for all combinations of RAP and HMA, (RAP/HMA percent: 0/100, 20/80, 30/70, 40/60, 50/50, 70/30, and 90/10). Prior to preparing the mixes, bitumen extraction was undertaken on the RAP material collected from the site, together with determination of the gradation of the aggregates.

Information about methods of recycling old asphalt was synthesised using the systematic review approach. However, the findings of the systematic review relate mainly to developed countries; there is, therefore, the need to assess the applicability of using RAP in developing countries. Based on the finding of the systematic review a questionnaire was developed to evaluate asphalt pavement recycling methods that can be implemented in Ethiopia. It was distributed to local and international experts in the field of pavement and materials' engineering with expertise in asphalt pavement recycling technology. The results of the questionnaire were analysed in conjunction with the importance factors of the criteria obtained using the AHP method as described in Chapter 5.

Finally, implementation of asphalt pavement recycling can be challenging where traditionally the focus is on using virgin materials in road construction, with little or no recycling of old road pavements. Therefore, in order to encourage the use of RAP, it is considered important to implement a high-level policy framework. In order to address this, a questionnaire was developed and distributed to decision makers at or above the level of directors and managers. The results were analysed to develop major policy statements for recycling asphalt pavements. This chapter of the thesis thus focuses on the results and discussions of the works carried out on economic analysis, laboratory investigation of samples containing RAP materials, development of selection criteria and policy framework.

5.2 Life Cycle Cost Analysis

Over the last decade the price of bitumen has been rising and it is forecast that it will continue to rise (Tradingeconomics.com, 2023). The increasing cost also applies to the aggregate used in pavement construction. These increases in costs are imposing very high pressure on road construction and maintenance operations. On the other hand, the cost of RAP material is small compared to both the cost of aggregate and bitumen as it only involves the removal and processing costs, otherwise it can be available for free. In addition to this, in the case of most asphalt pavement rehabilitation projects in Ethiopia dumping sites for the removed asphalt pavement materials are not readily available; thus, availability of RAP availability is currently not a problem for pavement rehabilitation projects in Ethiopia.

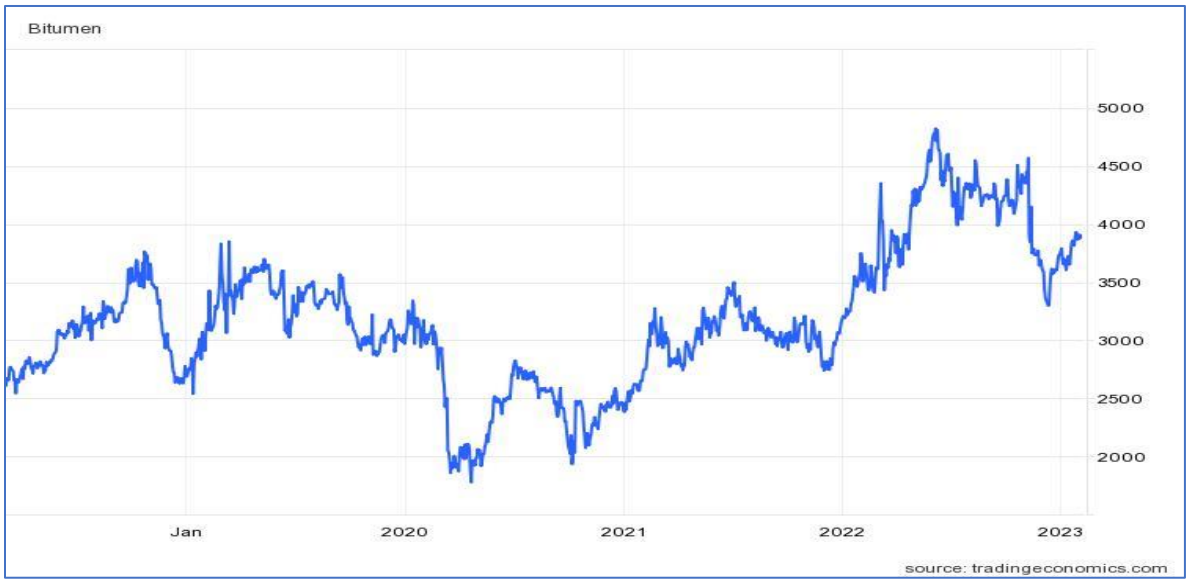


Figure 5-1 Bitumen price trends for the last five years
(https://tradingeconomics.com/commodity/bitumen)

When considering alternative ways of pavement rehabilitation, the most significant criterion was the cost saving that will be obtained, without compromising performance. In the case of asphalt pavement recycling, cost saving can be attributed to many factors, including its availability for a particular rehabilitation project, production process, transportation and placement of the mix on the road. The cost savings can also arise from the initial construction and maintenance and improvement costs through the design life of the pavement. Therefore, the economic advantage of recycling was analysed by comparing the initial construction of pavement with RAP

containing mixes of different proportions and the life-cycle costs for the same mixes. In this research, the analysis was made to assess the economic advantages of using RAP as an alternative for pavement rehabilitation using HDM-4 software.

The analysis was carried out in terms of net present value (NPV) and life cycle cost. Alternatives for the life cycle cost analysis are designed as proportions of RAP materials in a new asphalt mix. The base case has no RAP material and is used as a baseline for comparison. A low percentage below 20% RAP is not considered in this research as this has been covered in many previous works and proved to be viable options both in terms of cost and technical performance, though it may depend on the type of recycling method. Moreover, the literature indicates that better economic advantages may be obtained by using more RAP materials, so it is necessary to see how they perform as the amount increases in the HMA mix.

Different climatic conditions are considered in the analysis to investigate the effect on economic performance of recycled materials in the HDM-4 analysis. Three different climatic conditions: semi-arid, sub-humid and tropical-humid are considered in the analysis for all alternatives. The analysis process data, used in the HDM-4, are collected or obtained from the Ethiopian Roads Administration and for those not available, default values in the software are maintained. The economic analysis is carried out for a 20-year period with a discount rate of 12%. Alternatives designed for the purpose of analysis are presented in Table 5.1.

Table 5-1 RAP alternatives

Alternatives	RAP %
Base case	0
1	20
2	30
3	40
4	50
5	70
6	90

5.2.1 HDM4 input data

5.2.1.1 Calibration factors

Calibration factors used in this research are those recently calibrated for the Ethiopian conditions by (Berhanu, 2022). Those factors with high sensitivity class are used as shown in the Table 5-2. and for all other factors the default values are maintained.

Table 5-2 HDM-4 calibration factors (Berhanu, 2022)

Pavement type	Traffic level	Crack initiation K_{ci}	Crack progression K_{cp}	Rut depth progression K_{rp}	Roughness age environmental coefficient (K_{gm} /K_{ge})	Roughness progression factor K_{gp}
AC*	High	1.1	0.91	1.00	0.87	1.00

*Asphalt Concrete

5.2.1.2 Road geometry

The road section considered in this research is the 116 km long, A5-6, Bedele – Metu trunk road, located in the south-west of Addis Ababa. The geometric parameters of the road section considered are shown in Table 5-3.

Table 5-3 Road geometry data

Geometric Parameters	Unit	Values
Rise and fall	m/km	23
No. of rises and falls	No./km	30
Superelevation	%	2.5
Avg. horizontal curvature	Deg/km	15
Acceleration noise due to driver and road alignment	m/s^2	0.1
Speed limit	Km/hr	100
Speed limit enforcement		1.1
Altitude	m	2300

5.2.1.3 Traffic data

Traffic data for the analysis in HDM-4 was obtained from the ERA annual traffic count data for the A5-6, Bedele – Metu Road. The traffic class is high as the road section is carrying a traffic volume of AADT of over 7000 based on the ERA standard design guide (Ethiopian Roads

Authority, 2013). A traffic count was carried out in three cycles and a summary of the annual count, shown in Table 5-4, was used.

Table 5-4 Traffic count data

Name	**Class**	**AADT**
Small car	Passenger car	1125
Land rover	Utilities	500
Small bus	Buses	1125
Medium/heavy bus	Buses	1200
Small truck (2 axles, < 3.5 tons)	Trucks	1000
Medium truck (2 axles, >3.5ton)	Trucks	1125
Heavy truck (Multiple axles)	Trucks	750
Truck and trailer 4, 5, >5 axles	Trucks	911
	Total	**7168**

5.2.1.4 Road condition data

The road condition data was obtained from the annual road condition surveys carried out by the ERA Road Asset Management Department for the road section modelled in this study. For parameters not collected during the field surveys – texture depth, rut depth standard deviation, and skid resistance (SCRIM) – default values in HDM-4 were used.

Table 5-5 Pavement condition data

Condition Parameters	**Unit**	**Values**
Roughness (IRI)	m/km	6.5
All structural cracks	%	16.37
Wide structural cracks	%	13.72
Thermal cracks	%	0
Ravelled area	%	69.66
Number of potholes	No./km	90
Edge break area	m^2/km	111.43
Mean rut depth	mm	22
Rut depth standard deviation	mm	11
Texture depth	mm	0.5
Skid resistance (SCRIM 50km/hr)	-	0.4
Drainage	-	poor

5.2.1.5 Improvement and maintenance standard

The maintenance standard used in this analysis is routine and periodic maintenance interventions through the 20 years of the analysis period. For periodic maintenance a thin overlay of 25 mm is considered and the intervention will be every 6 years. Routine maintenance is carried out every year and activities included are

- Drainage maintenance
- Edge repair
- Pothole patching
- Crack sealing and miscellaneous items

The improvement work is an overlay of asphalt concrete over the granular base (AMGB) in HDM-4. This is considered to be pavement rehabilitation work where the existing asphalt surface is removed and the base is reconstructed and overlaid by a new hot mix asphalt (HMA) of 50 mm.

5.2.2 HDM-4 results and analysis

Economic analysis in HDM4 yields that in all alternatives the net present value (NPV) increases as a percentage of the RAP increased in the mix, as expected. In the systematic literature review it was shown that material cost saving increased as the percentage RAP in the mix was increased. In the HMA the substituted virgin material will have lower production and transportation costs compared to the production of virgin materials. If the RAP material is used in the base or subbase a direct substitution of the volume of material will give the highest cost saving, especially when the highest percentage of RAP is used. The result for different climatic conditions varies and the highest NPV is obtained for a tropical-humid climate. A summary of the NPV for all alternatives for three different climatic conditions is provided in Table 5-6.

Table 5-6 Summary of NPV for alternatives

Alternatives	NET Present Values (NPV) in Millions ETB		
	Semi-arid	Sub-humid	Tropical-humid
Base case (0% RAP)	0.00	0.00	0.00
20% RAP	26.050	19.240	9.047
30% RAP	62.978	76.225	80.660
40% RAP	102.192	135.037	155.536
50% RAP	142.708	195.980	233.247
70% RAP	209.625	272.870	330.628
90% RAP	804.399	1066.904	1229.837

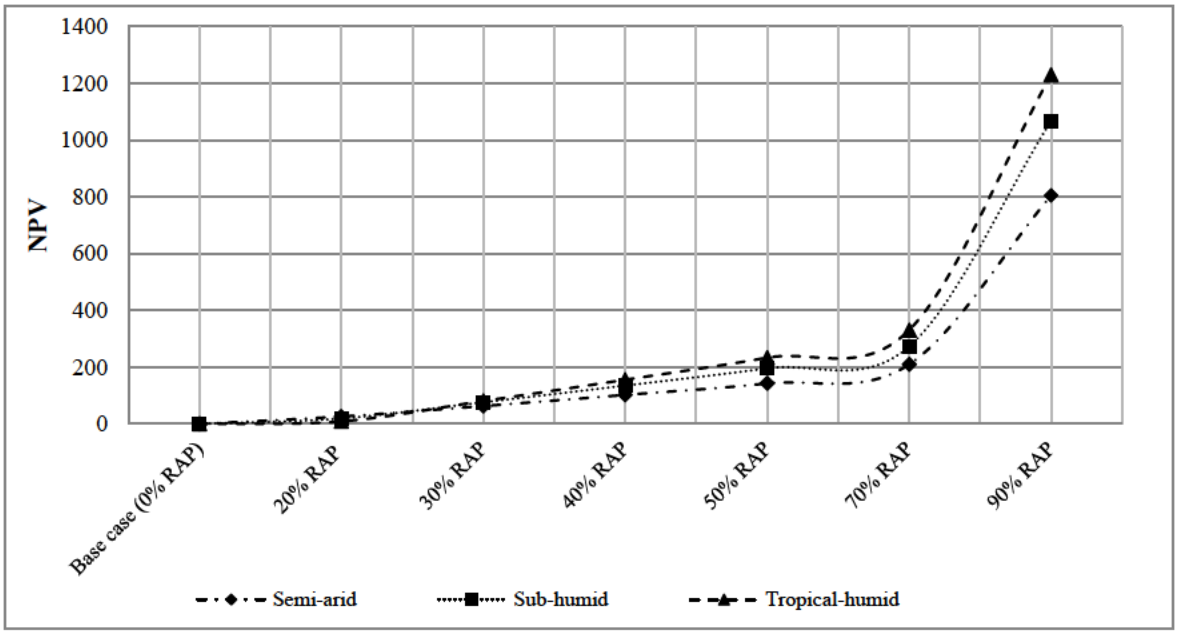


Figure 5-2 Relationship between NPV and RAP content

Recycling pavement materials in larger quantities gives a better economic advantage as seen from the results. All NPV values are positive for all alternatives and have an increasing trend as the %RAP increased. This shows, in general, recycling in any proportion is advantageous in economic terms. More economic benefit is observed for over 50% RAP materials used in the asphalt mix and the highest results of NPV are for 90% RAP in all climatic conditions. The highest NPV is recorded for the tropical-humid climatic condition compared to the other two climatic conditions, semi-arid and sub-humid. The NPV for tropical humid climates exceeds the NPV for semi-arid by 425% and sub-humid by 163%.

Cost effectiveness is one of the suitability criteria used in the recycling method selection development in this research, as shown in Table 5-7. The analytical hierarchy process (AHP) method has been used to generate a matrix for the evaluation of selection criteria and the pair-wise ranking method is carried out to evaluate each of the suitability criteria with each other and their preference over the others. Accordingly, as indicated in Table 5-7, cost effectiveness has scored the highest mark, indicating it is the most important criteria in selecting the asphalt pavement recycling methods identified. The HDM-4 analysis also confirmed that recycling of asphalt pavement is cost effective and recycling with larger proportions in the asphalt mix will give the highest economic advantage.

5.2.3 Life cycle cost analysis

The life cycle cost analysis was conducted to evaluate the long-term economic efficiency of alternatives, and assess which would give the lowest long-term cost in relation to the proportion of RAP in the HMA for pavement rehabilitation. Accordingly, HDM-4 was used to carry out the analysis based on the input parameters described above and an analysis period of 20 years at a discount rate of 12%. The discount rate for Ethiopia is obtained from the African Development Bank web site.

The Life Cycle Cost Analysis in HDM-4 considers the costs of Road Agency for maintenance and improvement works, Road User Costs in terms of Vehicle Operating Cost (VOC), passenger time costs, and road accidents cost. This is a project level analysis and it is made for the recycling alternatives shown in Table 5-1.

- The analysis period is for 20 years
- The analysis period starts at the beginning of 2022.
- The currency used is Ethiopian Birr (ETB)
- The road is a section of a Trunk Road
- The surfacing is Asphalt Concrete (AC)
- Three climatic zones are used (Semi-arid, Sub-humid and Tropical-humid)

The detailed definitions and input parameters such as geometry, pavement condition, traffic of the analysis is presented in Tables 5-3, 5-4, and 5-5

Analysis by options/alternatives is conducted by comparing the RAP performance with the base case (0% RAP). Figure 5-3 shows the results of the analysis considering the three climatic conditions and RAP percentages and the discussion is presented as follows.

Table 5-7 cost components for recycling alternatives

Alternatives	Economic cost (million ETB)	Financial costs (million ETB)
Base Case (No RAP)	11.6	13.4
20% RAP	10.2	11.7
30%RAP	9.4	10.8
40&RAP	8.7	10.0
50%RAP	7.9	9.1
70%RAP	6.4	7.4
90%RAP	5.0	5.7

In the analysis the cost components of each alternative indicated in Table 5-7. the unit rates used for the improvement works and the maintenance works are based on ERA's current unit rates for similar works.

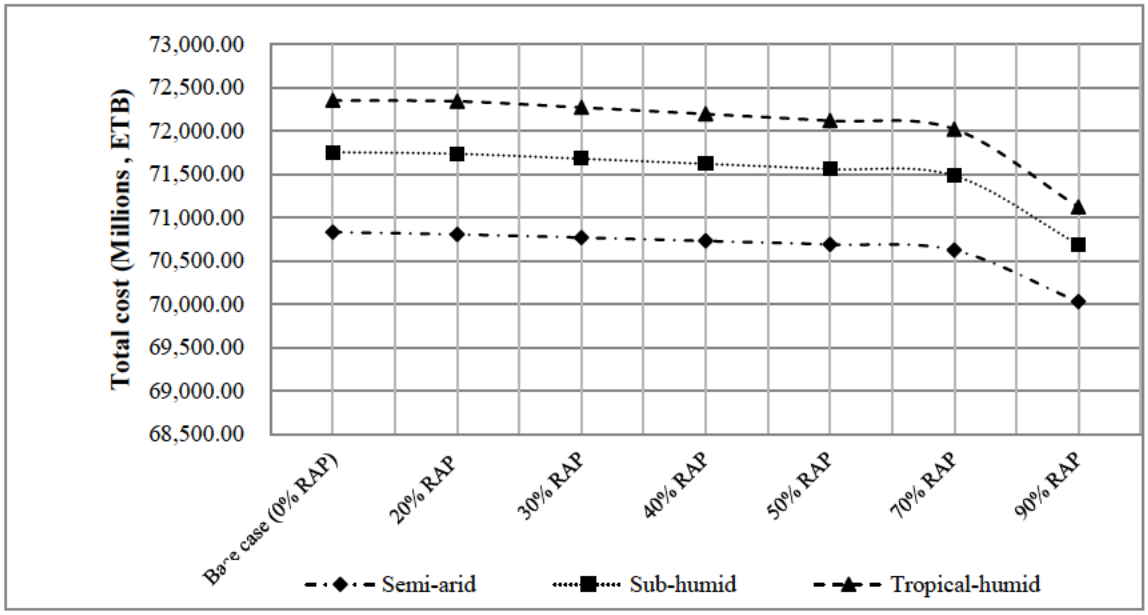


Figure 5-3 Total life cycle cost for %RAP

5.2.3.1 20% RAP

As discussed in this thesis, the lower percentage of the RAP in the asphalt mix have shown, in many research works, that it gives an equal or better performance compared with virgin asphalt mix or HMA. Table 5.6 shows that the NPV for 20% RAP was higher than HMA without RAP (base case). The NPV of 26.05 million was obtained for the semi-arid climate, while an NPV of 9.05 million was obtained for the tropical-humid climate condition, which shows that adding 20% RAP is of better economic value by over 9%, considering the minimum NPV of the three climatic conditions' value.

In terms of life cycle cost, a slightly lower total cost than the base case was obtained for 20% RAP (lower by only 0.04%). Comparing the LCC for the three climatic conditions, the cost saving was obtained for the semi-arid condition, which was lower than the base case by 0.04% and the minimum cost saving was for the tropical-humid that was 0.01% cost saving on the total LCC. Although, the cost saving on the LCC was negligible, it is evident that with the other advantages of using the RAP material constant, it is also an added benefit getting equal or lower values of total life cycle cost.

5.2.3.2 30% RAP

By using 30% RAP material in the asphalt mix, the NPV of 80.66 million for tropical-humid climatic condition was obtained as a maximum value. The lowest NPV was 62.98 million for the semi-arid climatic condition, while the sub-humid climatic condition had an NPV of 76.225 million. In all cases for 30% RAP material used in HMA, the NPV compared to the base case was positive and a higher benefit was obtained. It is also shown that the tropical-humid condition gives a higher economic benefit by 4% and 18% compared to sub-humid and semi-arid climatic conditions respectively.

The LCC for 30% RAP compared to the base case was slightly lower than it was for the 20% RAP. Compared to the base case, the maximum saving on the total LCC was obtained for the tropical-humid condition; unlike for 20% RAP (where the maximum cost saving was for the semi-arid climate), which was lower by 0.11%. The minimum cost saving was for semi-arid which was lower by only 0.09%. Note that in all cases of the climatic condition, a lower total LCC was obtained for 30% RAP usage compared to the base case, that is without the RAP mix.

It is also to be noted that the maximum NPV and lower total LCC were obtained for the tropical-humid climatic condition.

5.2.3.3 40% RAP

A maximum NPV of 155.536 million was obtained for the tropical-humid condition for 40% RAP used in the HMA mix, and a minimum of 102.192 million for the semi-arid climatic condition. As it was for the 20% and 30% RAP, the NPV for the 40% RAP was also positive and the highest value was obtained for the tropical-humid climatic condition. The tropical-humid NPV was higher by 20% and 53% from the semi-arid and sub-humid climatic conditions respectively, which also shows that the difference is increasing compared to the 30% RAP case (which was higher by 4% and 18%).

In this case also the total LCC was lower from the base case by a small amount. The tropical-humid was still showing the biggest decrement from the base case, by 0.21%, and the semi-arid was lower by 0.14%, with the sub-humid lower by 0.19%. The tropical-humid climatic condition showed the highest NPV and lowest total LCC in the case of 40% RAP usage.

5.2.3.4 50% RAP

Use of 50% RAP in the tropical-humid climatic condition has shown a high NPV value of 233.247 million; while the semi-arid condition showed an NPV of 142.708 million. It is evident so far that as the percentage of RAP increased the NPV was also increasing for all climatic conditions considered in this research. The tropical-humid climatic condition still showed a higher NPV compared to the others and was 91% higher from the sub-humid and 37% higher from the semi-arid climatic condition. This shows that the highest RAP proportion is more suitable in terms of cost saving in the tropical-humid climatic condition.

The total LCC saving was comparatively increasing as the RAP percentage in the mix increased: for the tropical-humid 0.32%, sub-humid 0.27% and 0.20% for the semi-arid climatic conditions was observed for the 50% RAP case compared to the base case. In the case of 50% RAP case the tropical-humid has shown a lower total LCC and higher NPV values.

5.2.3.5 70% RAP

Increasing the proportion of RAP material in the HMA mix has shown higher values of NPV for all climatic conditions. While the tropical-humid was still exhibiting the highest values and in the 70% RAP proportion, with an NPV of 330.628 million; for the sub-humid 272.87 million; and for the semi-arid 209.625 million was obtained, indicating that RAP use is still more favourable in the tropical-humid climate. It is higher than the sub-humid by 58% and the semi-arid by 121%, indicating the difference was increasing and RAP may be more economical both in terms of proportion and cost saving.

The same trend was observed for the total LCC. The tropical-humid shows the highest saving of the total LCC that is 0.46% lower compared to the base case, and 0.38% and 0.30% lower for the sub-humid and semi-arid climatic conditions respectively. This shows that the highest NPV and lower LCC was obtained for the tropical-humid climatic condition.

5.2.3.6 90% RAP

The highest proportion of RAP in this research is 90% and the economic analysis shows that it has the highest economic advantage compared to the base case and the rest of the percentages of RAP in the HMA mix. This confirms that the higher proportion of RAP in the HMA mix gives a higher economic return as indicated in the literature reviewed in this research. An NPV of ETB 1.23billionwas obtained for the tropical-humid, ETB1.07billionfor the sub-humid and 804.4 million for the semi-arid. Compared to each other, the tropical-humid was higher by 425% and 163% from the sub-humid and semi-arid climatic conditions respectively.

Savings on the total LCC was maximum for 90% RAP, where it was higher from the base case by 1.7% for the tropical-humid, 1.49% for the sub-humid and 1.14% for the semi-arid climatic conditions. These results are higher compared to the other RAP proportions in the HMA mix and also from the base case. It shall be noted that the total LCC in all cases is lower compared to using a new HMA mix in asphalt pavement rehabilitation.

5.2.4 Summary

The following points summarise the discussion made on the economic analysis.

i. The NPV is positive in all alternatives indicating use of recycled materials is an economical viable approach.
ii. The economic analysis confirmed that cost savings should be the top criteria for selection of recycling methods, as indicated in the literature review and the developed selection methodology for selecting recycling methods.
iii. The analysis also confirmed that using a higher proportion of RAP materials in HMA mixes gives better economic benefit as indicated in the systematic literature review.
iv. Although the variation looks small in terms of saving in the total LCC compared to the base case, use of recycled materials or recycling of asphalt pavement in the pavement rehabilitation process is advantageous.
v. It is more advantageous to recycle asphalt pavement in a tropical-humid climatic condition. The reasons could be that the use of virgin materials and maintenance works are more frequent in this climate compared to the others, and by using fewer virgin materials means added advantages that lower the total LCC and give the highest NPV values.
vi. Recycling of asphalt pavement with a high percentage of RAP materials is economical and gives a higher benefit. Using 90% RAP in HMA mix gives the highest economic benefit.

5.3 Laboratory experiment results

The main reason for the laboratory investigation was that during the literature review it was apparent that there was a paucity of information on the performance of recycled material in pavements that related to sub-Sharan Africa. It was thus necessary to conduct performance related tests in the laboratory to add to the existing meagre data.

In the methodology formulation stage, the laboratory testing procedure and work flow diagram were developed and followed to conduct the selected tests. The different tests planned to determine the performance of RAP materials in asphalt mixtures are:

a. Indirect tensile strength
b. Resilient modulus test
c. Permanent deformation and

d. Marshall stability

The results of the tests are discussed in the following sections. The mix proportions of the RAP materials in the HMA are as shown in Table 6.1.

The first stage of testing was to understand the existing pavement materials through extraction of bitumen and particle size distribution analysis of RAP aggregates.

5.3.1 Bitumen extraction and particle size distribution (PSD)

The AASHTO T164A test method using a centrifuge extractor was employed to extract bitumen from the RAP samples. After extraction, the residual bitumen characteristics were supposed to be determined, however, due to a lack of appropriate chemical for the extraction it was not possible. Thus, benzine was used to extract the bitumen, though its characterisation was not possible. It was only possible to do one extraction at the Chinese road materials laboratory based in Ethiopia to determine the penetration of the bitumen in the RAP.

Particle size distribution (PSD) analysis was undertaken on the aggregate extracted from the RAP and checked against the asphalt wearing course mix gradation for new mix preparations, based on the Ethiopian Roads Administration specification (Ethiopian Roads Authority, 2013). It should be noted that during the test specimen preparation maximum care was taken so that no crushing of the aggregates happened and the PSD of the old pavement aggregate was not altered in the process. Figure 5-4 shows the PSD of aggregate extracted from the samples taken for this research at the RRC. Figure 5-4a shows the reclaimed asphalt pavement that is carefully disintegrated and no crushing of stones has happened in the process; while Figure 5-4b shows the result of sieve analysis.



Figure 5-4a RAP material: hand crushed-



Figure 5-4b RAP material aggregate: after binder extraction is done [1 – 75µm, 2 – 150µm, 3 – pan, 4 – 300µm, 5 – 5mm, 6 – 9mm, 7 – 12mm, 8 – 14mm, 9 – 19mm]

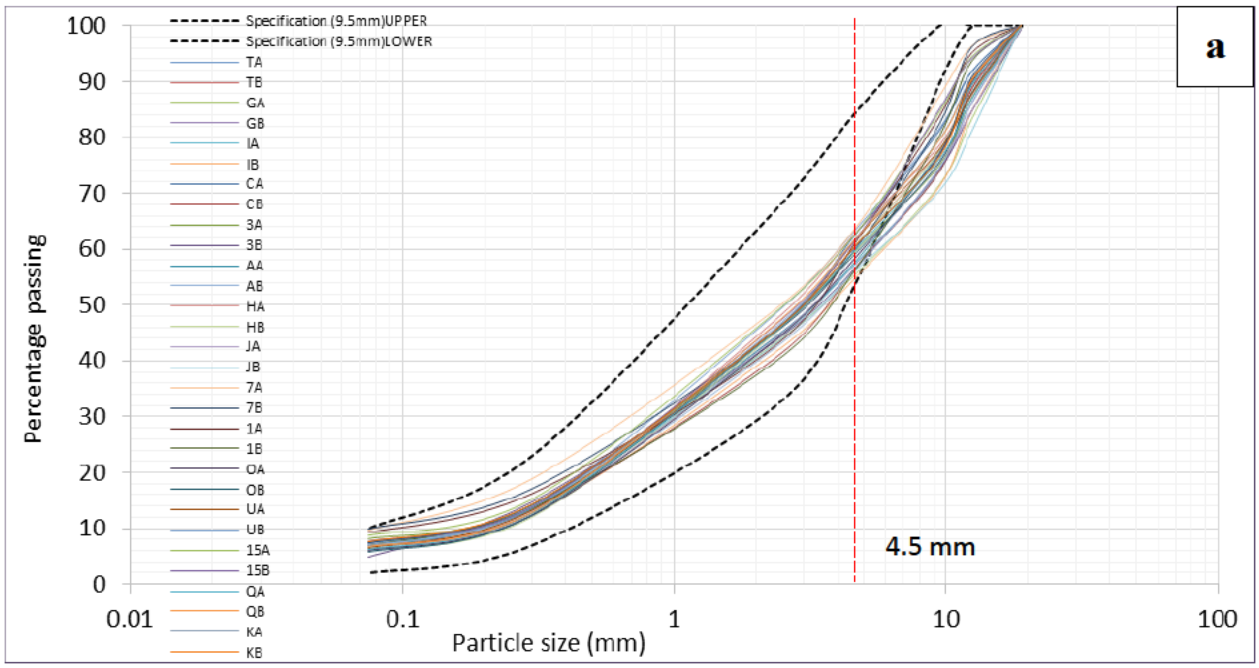
Figure 5-4 RAP material used in this study

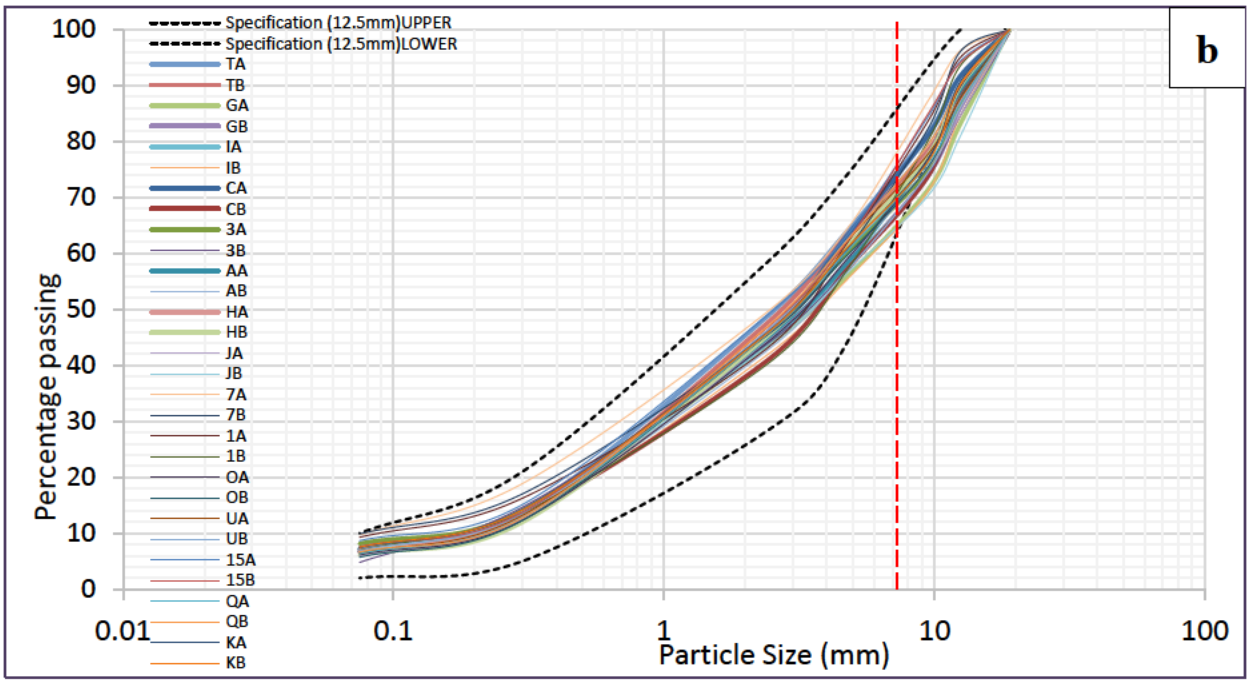
The ERA specification (Ethiopian Roads Authority, 2013) provides the gradation envelope for the surfacing asphalt mix as shown in Table 5-8. The mixes containing RAP were designed for the asphalt wearing course using the continuously graded asphalt concrete as per the ERA standard specification Thirty extraction tests were conducted on samples collected from existing road pavements, and PSD determinations were undertaken for all of them. This helped to assess if the RAP aggregate gradation after extraction had changed and the extent of its deviation from the specification, so that corrections/adjustments could be made in designing the new mix containing RAP.

Figure 5-5c shows that the PSD of RAP aggregates fit the 19 mm nominal maximum aggregate size grading envelope, however, it is near the upper boundary in the specification. For 12.5 mm and 9.5 mm nominal maximum aggregate size, aggregates sizes below 4.5 mm fit within the upper and lower boundaries; whereas, sizes greater than 4.5 mm aggregate fall below the lower limit. For 12.5 mm nominal maximum aggregate size, aggregates sizes below 7.5 mm fit within the upper and lower boundaries; whereas, sizes greater than 7.5 mm aggregate fall below the lower limit.

Table 5-8 Particle size distribution for AC wearing course (ERA, 2013)

Sieve size (mm)	Nominal maximum stone size (mm)		
	Percentage passing sieve		
	19	12.5	9.5
25	100		
19	90 – 100	100	
12.5	-	90 – 100	100
9.5	56 – 80	-	90 – 100
4.75	35 – 65	44 – 74	55 – 85
2.36	23 – 49	28 – 58	32 – 67
0.300	5 – 19	5 – 21	7 – 23
0.075		2 – 10	2 – 10
Bitumen content (%)		4 – 11	5 - 12





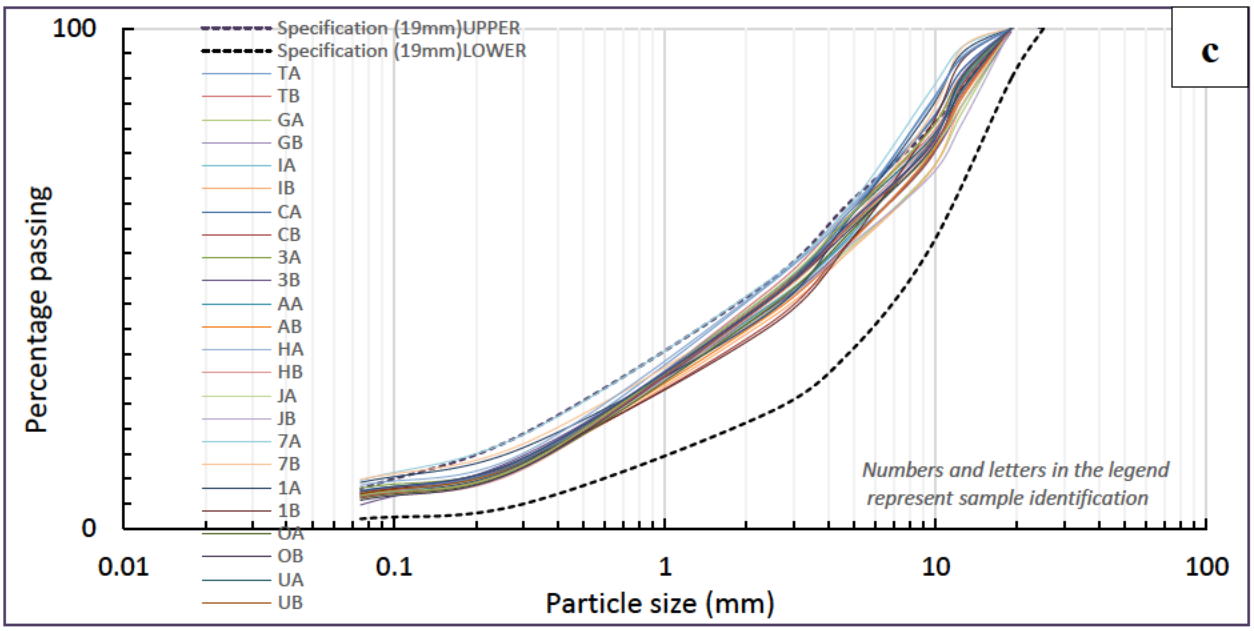


Figure 6 1a, b, c PSD for 9.5mm, 12.5mm and 19.5mm nominal maximum aggregate size

5.3.2 Bitumen content

The average bitumen content of RAP determined from the extraction tests was 4.63%. within the range of (5.58 – 3.72%). Penetration of RAP bitumen was determined after the solvent was

removed from the extracted bitumen and found to be 18.5. Penetration was carried out on one sample at the Chinese laboratory in Ethiopia due to a lack of extraction chemicals at RRC. It is also assumed that the type of bitumen is the same for all samples obtained from the field and the property such as penetration would be the same. The optimum bitumen content as obtained used in the mixes for the Marshall test was 5%. Stability and flow values are the main characteristics desired for each of the mixes containing different proportions of RAP. The RAP binder that contributes to the mix was determined based on the extraction test results and their contribution is as shown in Table 5-9.

Table 5-9 Contribution of RAP binder

RAP (%)	0	20	30	40	50	70	90
RAP bitumen in the mix (%)	0	0.99	1.47	1.94	2.41	3.32	4.20

From the penetration test result (18.5) the RAP binder is a higher viscosity binder. Therefore, based on the climatic condition and elevation from where the existing RAP was collected, it was decided that 60/70 penetration grade bitumen would be used for preparation of the mixes.

5.3.3 Marshall test

5.3.3.1 Preparation of control mix

The control mix was prepared with virgin materials to assess the effect of RAP material for performance evaluation. The Marshall method of design mix was followed based on the data from ERA. All the required tests were carried out on the control mix and they were later used for the purpose of comparing against the performance of the RAP containing mixes. The test results of the control mix are summarised in Table 5-10.

Table 5-10 Test results of control mix

Properties	Unit	Values
Binder content	%	5
Stability	KN	6.6
Flow	mm	2.13
Resilient Modulus	MPa	607.38
ITS	KPa	0.56
Rut depth	mm	1.65

5.3.3.2 Marshall test results

As noted in section 2.4 (Methodology), asphalt mixes containing 20%, 30%, 40%, 50%, 70%, and 90% of RAP materials and a control mix with no-RAP were tested. Results of these tests are shown in Table 5-11.

Table 5-11 Results of Marshall test

RAP %	Virgin Binder, %	RAP Binder %	Total Binder %	Bulk Density	SSD	Theoretical Density	Air Void %	V.M.A	V.F.A	Stability (KN)	Flow Unit (mm)
0	5.00	0.00	5.0	2.342	2.384	2.667	10.6	22.2	52.2	6.60	2.13
20	4.07	0.93	5.0	2.401	2.434	2.653	8.3	20.1	58.9	5.08	3.85
30	3.61	1.39	5.0	2.402	2.424	2.654	8.7	20.4	57.6	9.35	2.98
40	3.15	1.85	5.0	2.395	2.409	2.645	8.9	20.6	56.7	7.48	2.30
50	2.69	2.32	5.0	2.415	2.436	2.629	7.3	19.2	61.7	9.11	3.05
70	1.76	3.24	5.0	2.433	2.446	2.619	6.6	18.5	64.3	9.91	2.55
90	0.83	4.17	5.0	2.447	2.457	2.611	5.9	17.8	66.9	11.32	1.93

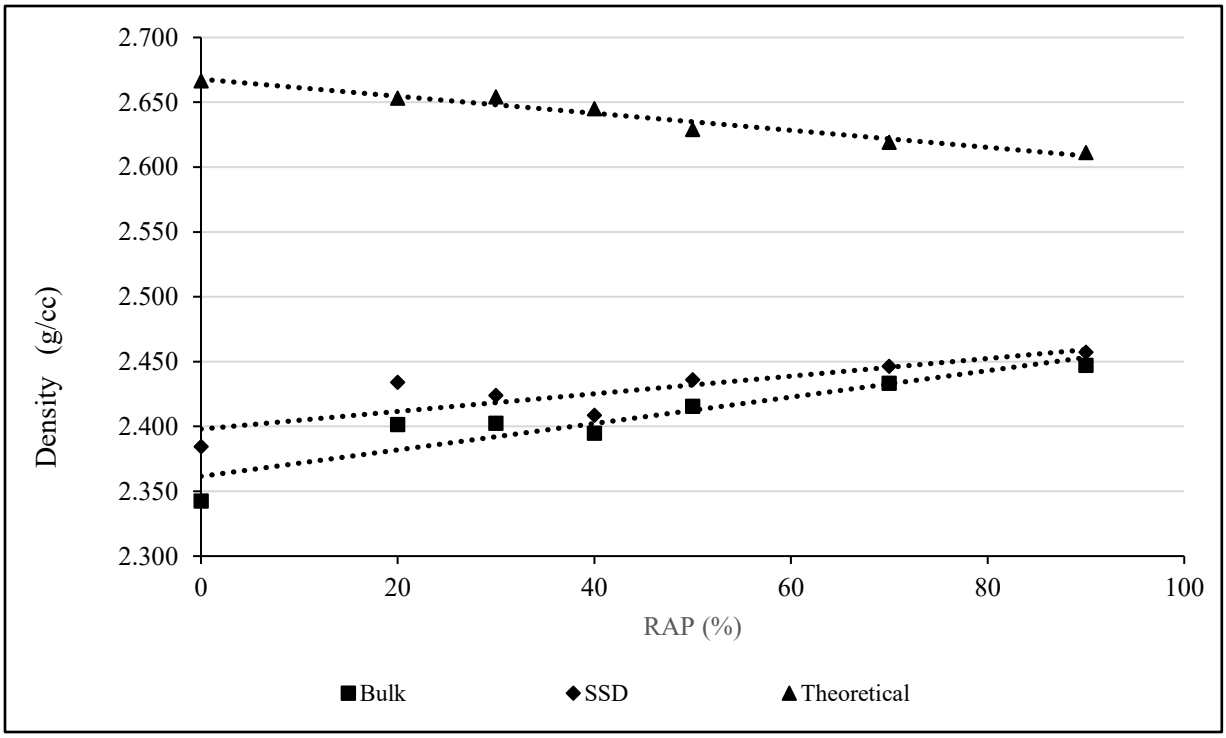


Figure 5-5 Density values for different proportions of R

As the percentage of RAP increased, the theoretical density value showed a decreasing trend, while the bulk and SSD showed an increasing trend.

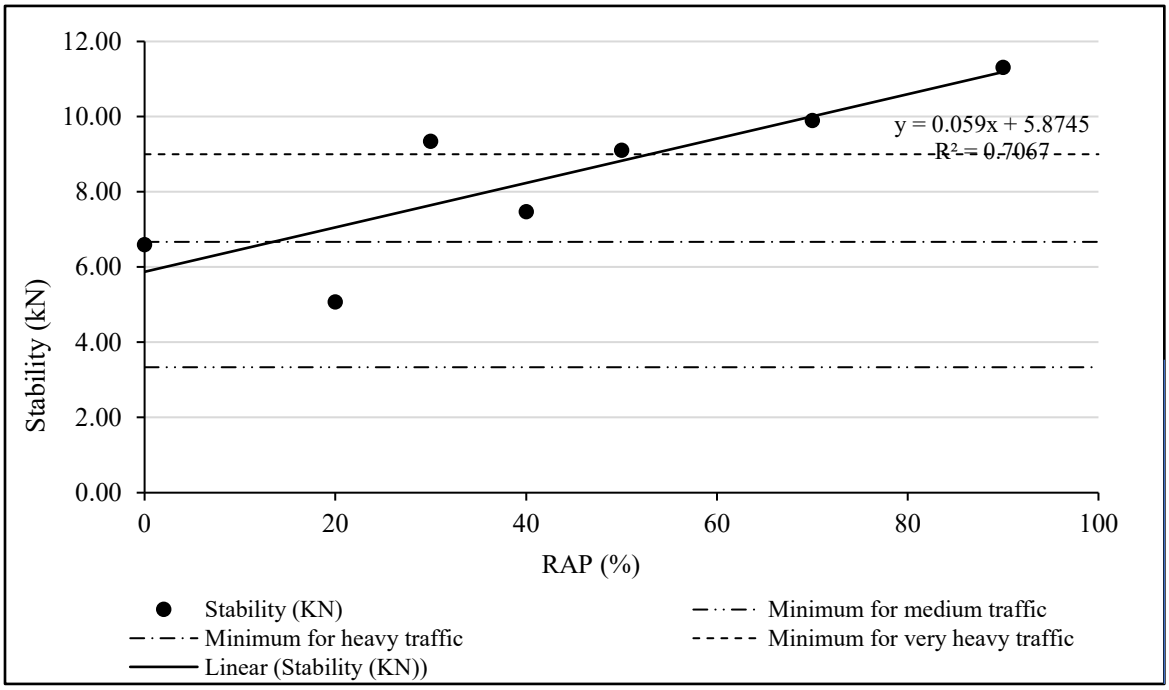


Figure 5-6 VMA and VFA values for different proportions of RAP

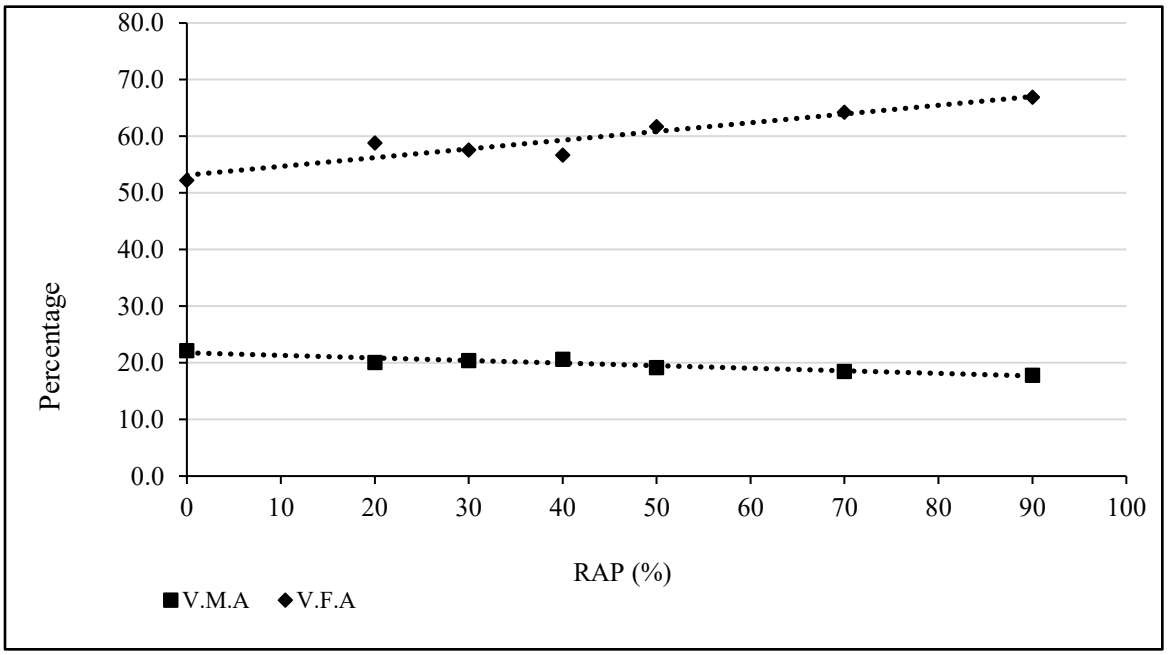


Figure 5-7 Results of stability of RAP containing mixes

Stability results for various proportions of RAP are shown in Figure 5-7. They show that over 54% RAP satisfied the stability requirements of the ERA specification for heavy traffic. Stability increased as percentage of RAP increased in the mix, however, adding RAP below 14% will have equal stability to the control mix.

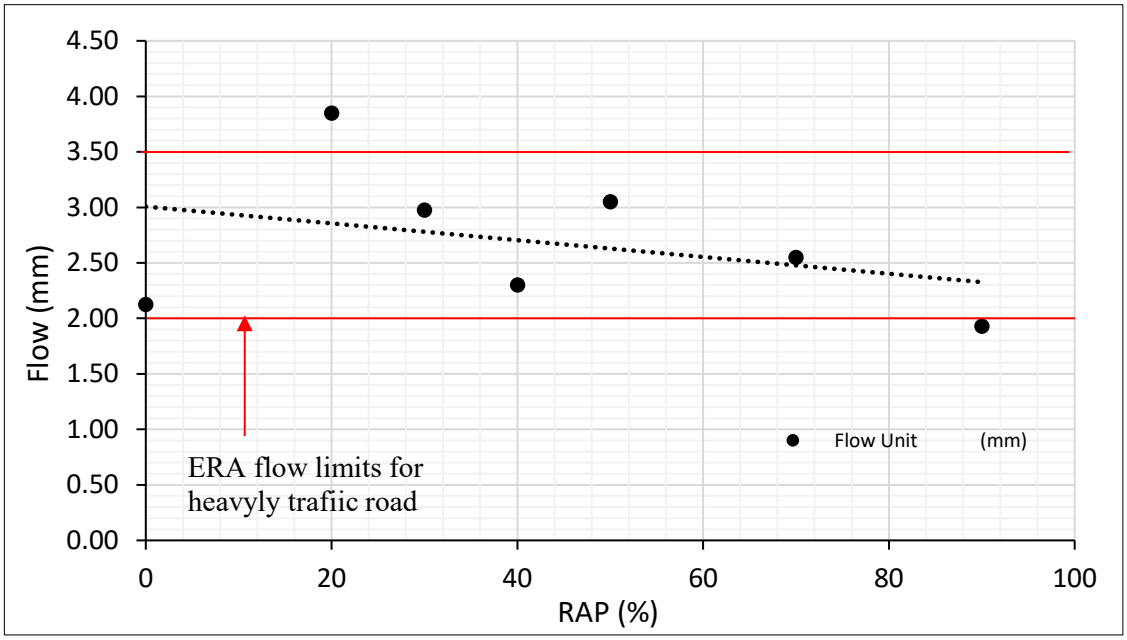


Figure 5-8 ERA Flow limits for heavy traffic road

The ERA specification of flow values for heavy traffic is between 2 and 3.5. Generally, flow values decrease as the percentage of RAP increases (Abdel-Jaber, et al., 2022) as expected. However, it increased at 50% of RAP and then started decreasing again. At 90% RAP the flow value fell below the minimum required value of 2 mm.

5.3.3.3 Summary of Marshall test results

- Stability and flow requirements for HMA containing RAP materials have non-conformity with the ERA specification requirement.
- For very heavy traffic RAP added in excess of 54% showed better stability.
- In general RAP added in excess of 15% had good stability for heavy traffic.
- Voids in the mix have shown higher values compared to the specification.

- Stability of the mix increased as %RAP increased in the HMA mix.
- RAP percentages between 20% and 90% have shown flow values within the specification requirement.
- Use of recycled materials from existing road pavement satisfies specification requirements of HMA mixes for pavements carrying high traffic volume.

5.3.4 Indirect tensile strength test

An indirect tensile strength test was used in this research as one of tests to evaluate the quality of the HMA containing RAP materials, to evaluate their cracking potential. An indirect tensile strength test was carried out according to ASTM D 6931 on an HMA mix containing RAP materials and on the control mix (mix with no RAP). Generally, higher tensile strain at failure means that the mix has good resistance to cracking compared to that of low tensile strain values. Test data for ITS is summarised and shown in Table 5-12. The test samples were prepared at the RRC, compaction is at 75 blows on each face of the sample using a Marshall hammer. The following equation was used to calculate the ITS:

$$ITS = \frac{2L}{\pi DT}$$

Where, L – applied load at failure

D – diameter of specimen

T – thickness of specimen

Table 5-12 Summary of input data for ITS test

Description	unit	values
Weight of aggregate used for the mix	gm	1200
Bitumen content	%	5
Specific gravity of bitumen		1.03
Specimen size *Height* *Diameter*	mm mm	64.3 101.4
Aggregate heating temperature	ºC	165
Virgin bitumen heating temperature	ºC	150
RAP heating temperature	ºC	130
Mixing temperature (RAP & virgin materials)	ºC	150
Specimen used for each test	No.	2
Compaction temperature	ºC	145
Marshall compaction	Blows on each side	75
Cool at room temperature		for 24hrs
Deformation rate	mm/min	50

Test results shown in Table 5-11 indicate that as the percentage of RAP materials in the mix increased, the resistance of cracking increased. The rate of increase in resistance to cracking as the percentage of RAP increased in the mix is higher and it is evidenced by the slope of the curve as shown in Figure 5-12. The ITS value of HMA containing 90%RAP increased by 112 compared to HMA without RAP, while it increased by only 2.6% for 20% RAP.

Based on the ITS values the elastic and resilient modulus of the mix are calculated. The elastic modulus was calculated using the following formula obtained from the Tanzanian Laboratory Testing manual (Tanzania Minstry of works, 2000).

$$E = 6.1 * ITS + 100 \quad (1)$$

Where: E – Elastic Modulus (Mpa)
ITS – Indirect Tensile Strength (Mpa)

Table 5-13 ITS test results

RAP, %	Bulk Density, KN/m3	ITS (MPa)	E - Modulus (MPa)	Density / strength (units)	Density /modulus	E/IDS
0	23.56	0.56	103.40	42.23	4.39	185.30
20	23.74	0.57	103.49	41.46	4.36	180.75
30	23.79	0.70	104.26	34.04	4.38	149.17
40	23.76	0.93	105.70	25.45	4.45	113.19
50	23.59	1.02	106.21	23.16	4.50	104.28
70	23.65	1.05	106.38	22.62	4.50	101.76
90	23.62	1.19	107.24	19.91	4.54	90.41

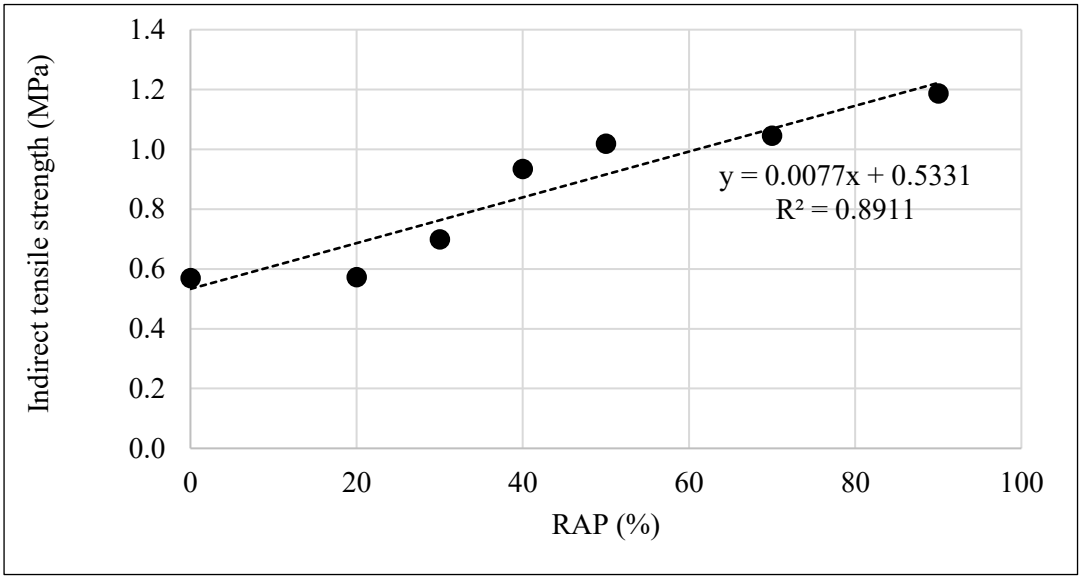


Figure 5-9 ITS test results

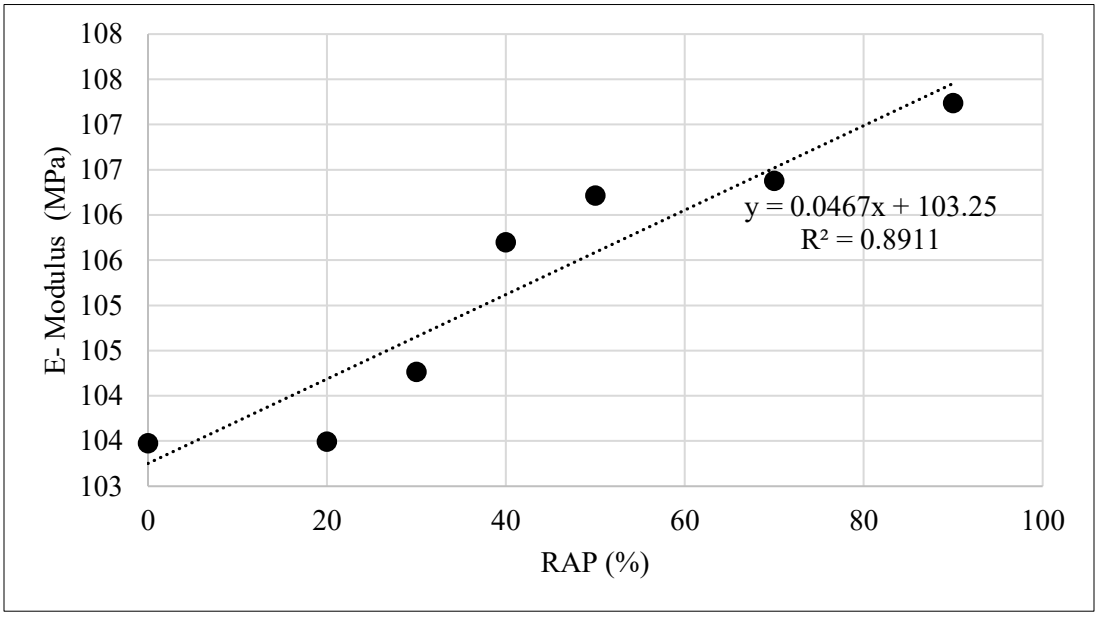


Figure 5-10 E-Modulus values

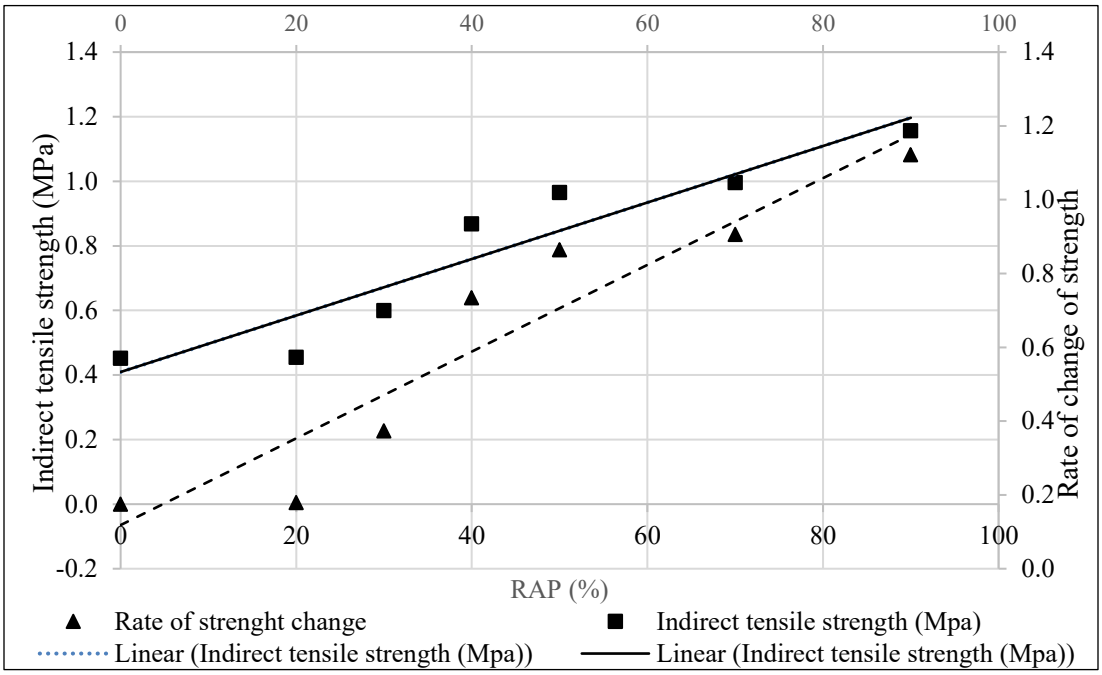


Figure 5-11 ITS rate of strength change

4.2.4.1 Summary of Indirect Tensile Strength test

The ITS test results indicate that as the RAP amount increased in the mix, the ITS value also increased showing that performance regarding resistance to cracking is improved. In summary:

- ITS values increase with the increase in RAP proportion in the HMA mix
- The rate increase in ITS value is much higher as the RAP increased in the mix. At 90% RAP the increase in ITS value is 112% compared to control mix while it is only 2.6% for 20% RAP in the mix.

Summary of indirect tensile strength test

The ITS test results indicate that as the RAP amount increased in the mix, the ITS value also increased, showing that the performance regarding resistance to cracking is improved. In summary:

- ITS values increase with the increase in RAP proportion in the HMA mix

- The rate increase in ITS value is much higher as the RAP increased in the mix. At 90% RAP the increase in ITS value is 112% compared to the control mix while it is only 2.6% for 20% RAP in the mix.

5.3.5 Resilient modulus (MR)

The elastic Modulus is used to evaluate the stiffness of the HMA containing RAP. The test was conducted on specimens with and without RAP. A specimen without RAP was used as a control mix and its results are the basis for comparing the stiffness of mixes containing RAP in different proportions.

Although it was desired to conduct the test for the resilient modulus, the apparatus was not available at the RRC, therefore the MR was calculated using formulae. Therefore, it was decided to obtain the values indirectly from the ITS test. However, the method used to calculate the MR in this research has short comings. The first is that the calculations are made based on the formula derived for repeated loading in the tension test apparatus, while ITS is calculated for the maximum loading at failure. This might not give the desired result which is the resilience of the material for repeated loading it may endure during its service life. Secondly, the results are not in conformity with the ITS test results though the MR is calculated based on it. The elastic modulus was calculated using the following formula obtained from the Tanzanian Laboratory Testing manual (Tanzania Minstry of works, 2000).

$$E = 6.1 * ITS + 100 \qquad (1)$$

Where: E – Elastic Modulus (units)
ITS – Indirect Tensile Strength (units)

M_R was calculated indirectly based on the ITS test results using the formula given in equation (2). Estimation of M_R values, were based on υ value of 0.35 and are shown in Figure 5-11.

$$MR. = \frac{P(v+0.2734)}{HT} \qquad (2)$$

Where: P – Maximum Load at failure (N)
υ – Poisson's ratio
H – Horizontal deformation (mm)
T – Thickness of specimen (mm)

20% and 30% RAP gave lower values compared to the mix without RAP (control mix). General trend, from 20 to 90% RAP content, is that as MR increase as the proportion of RAP is increased. This trend means that as the RAP portion increases in the mix, stiffness of the mix also increases. Maximum value of M_R is for mix containing 90% RAP and the minimum is for 20% RAP. The highest M_R value is more than the control mix by 132% and the lower M_R is less by 45% from the control mix.

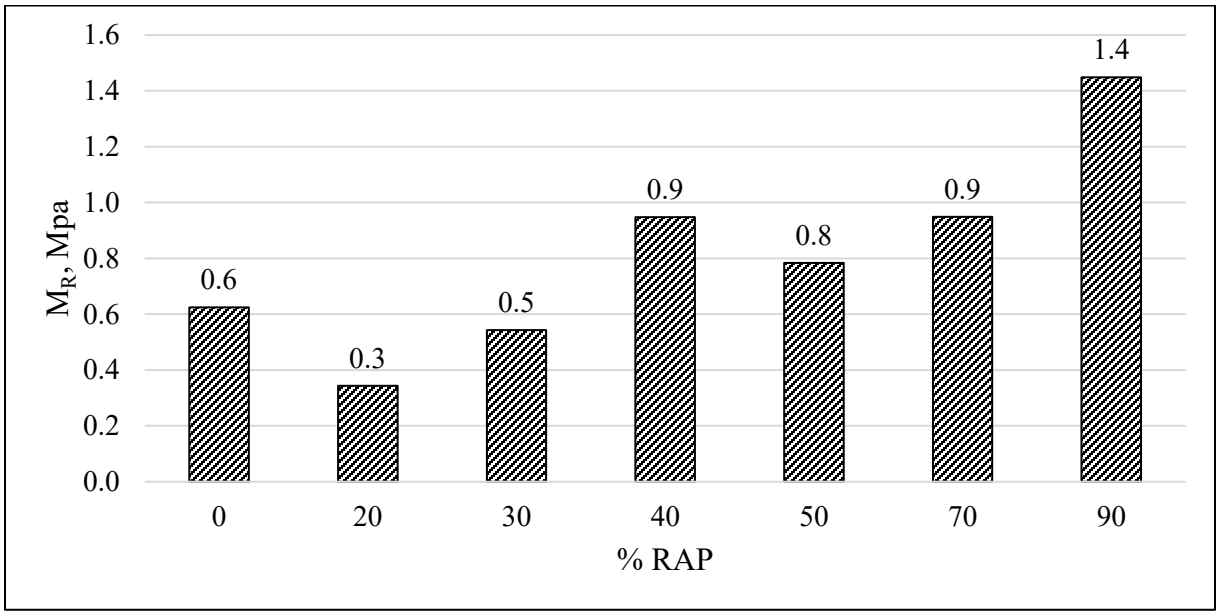


Figure 5-12 Calculated Resilient Modulus values

For ITS the results are increasing for all cases of RAP proportion, while it is not for M_R as the calculated results show some irregularity as shown in Figure 5-11. For 20% and 30% RAP lower M_R value than the control mix is obtained, then increased significantly for 40% RAP above the control mix and then decreased for 50% RAP and start to increase up to 90% RAP.

5.3.6 Rutting

The rutting potential of HMA containing RAP materials was measured using the wheel rutting equipment on specimens prepared and compacted using the slab compactor. Samples were prepared in sizes of 305 mm x 305 mm x 50 mm. The compacted specimens and the mould were cooled at normal room temperature for 24 hrs and then the samples and the mould were heated in an oven for 16 hrs at a temperature of 60 ºC. The samples were prepared by compacting them

using a linear kneading compactor with a compaction load of 800 N. Rutting was measured at 20,000 cycles with an applied load of 705± 4.5 N at 60 ºC using the wheel tracking tester machine.

Table 5-14 Measured rut depth at 20,000 passes

RAP (%)	0	20	30	40	50	70	90
Rut Depth (mm)	1.7	1.3	2.6	2.5	2.4	1.7	1.0

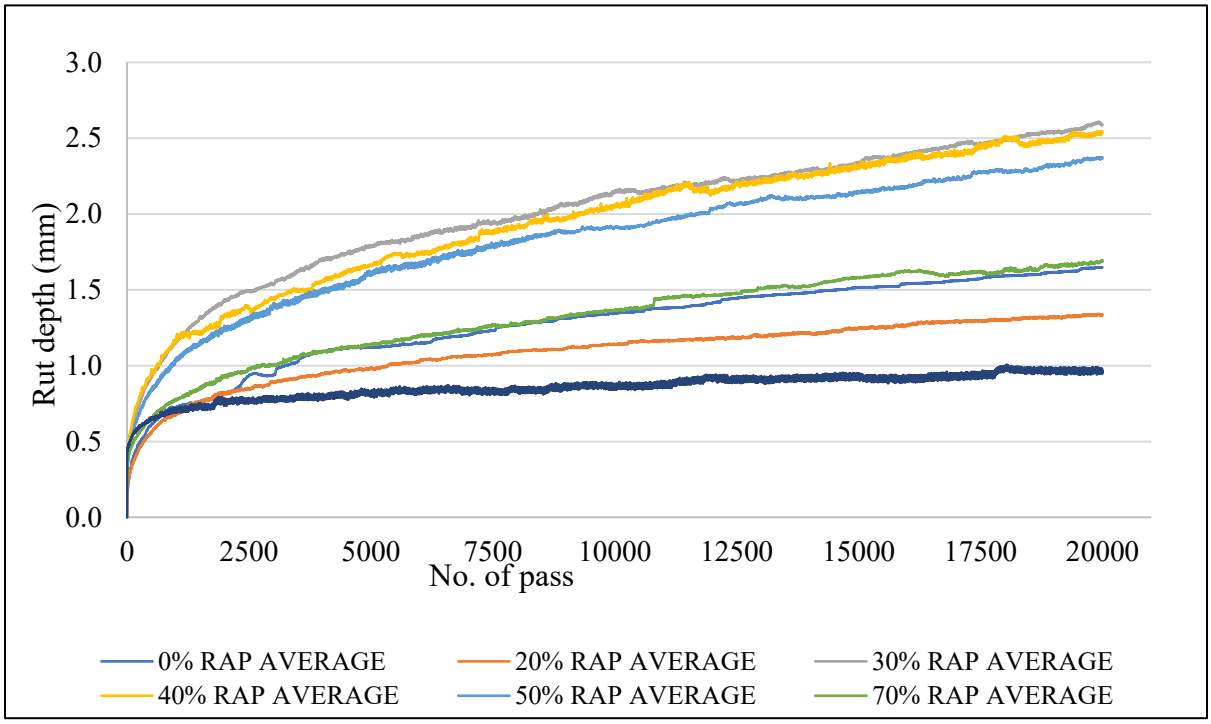


Figure 5-13 Rut depth at 20,000 passes for each RAP content

For the control mix (HMA without RAP) the rut depth was 1.7 mm and this is taken as a comparison value for the mixes containing RAP. The HMA with 90%RAP has shown the lowest rut depth of 0.95 mm; while 30% and 40% RAP had the highest rut depths of 2.58 mmm and 2.35 mm respectively.

In the rut depth measurement of HMA containing different proportions of RAP, it is observed that as the RAP increased in the mix the rut resistance of the mix showed improvement, especially on the higher proportion, compared to the control mix. However, it is also to be noted that mixes with 30%, 40%, and 50% RAP indicated rut depths higher than the control mix, while

20% RAP had a lower rut depth. The higher RAP proportions giving a lower rut depth is a good result, however, it should also be noted that cracks can be a problem as evidenced by the ITS result, where higher RAP content resulted in lower resistance to cracking.

Agree- so we need to give tentative recommendation in terms RAP that can be sued based on all the results we have. We also need include discussion on what other researcher have found as the optimum RAP content.

5.3.7 Summary of laboratory tests

The test results have demonstrated an improved performance of the HMA mix containing RAP material. The tensile strength has increased with the increase of RAP material in the mix. Rut resistance also increased with higher proportions of RAP, however, 30%, 40% and 50% RAP contents have showed higher rut depths compared to the control mix. In terms of the Marshall test results, stability of mixes increased with the increase of RAP material. Flow values have also improved with the increase of RAP.

With RAP increased in the HMA mix the performance of the mix has improved, indicating that recycling of old asphalt pavement material is a beneficial exercise. It is also to be noted that RAP material if properly prepared and used in asphalt mix has a high potential of improving the performance of the mix, such as the resistance to rutting and cracking. A summary of the laboratory tests on the HMA containing RAP materials:

i. Stability of the mix increased with RAP content in the HMA mix.
ii. Voids in the mix were higher compared to the specification.
iii. A RAP percentage between 20% and 90% has shown flow values within the specification requirement.
iv. Stability and flow requirements for the HMA containing RAP materials have non-conformity with the ERA specification requirement.
v. The performance of the mixes has increased with the increase of RAP materials in the mix.
vi. The mixes have shown better rut resistance characteristics for higher proportions, 70% and 90% of RAP, compared to the control mix. It is observed that 20%RAP has shown

better resistance to rutting, while 30%, 40%, and 50% RAP contents have shown lower rutting resistance compared to the control mix.

vii. Stiffness of the mixes have also increased with the increase of RAP content.

viii. The E-Modulus and ITS ratio gives a good correlation which shows use of recycled materials from existing road pavement satisfies specification requirements of HMA mixes for pavements carrying high traffic volume.

6 POLICY FRAMEWORK DEVELOPMENT

6.1 Introduction

During the initial stages of the Road Sector Development Program (RSDP), existing asphalt from the A1 trunk road was recycled and used as a base course. In a later stage a 65-km segment of the trunk road A4 was rehabilitated using foamed bitumen technology. These are the only recycling projects undertaken on the Ethiopian roads.

So far there is no guideline or policy framework for the implementation of asphalt pavement recycling in Ethiopia. One of the aims of this study was to develop a policy framework that is required for the successful implementation of asphalt pavement recycling in Ethiopia. Recycling is not well practiced due to various reasons, including the assumption that natural construction materials are abundantly available, which is masking the fact that natural resources are non-renewable and their uncontrolled use may affect the needs of the future generation. The other most important factor is the lack of a clear policy that guides the use of recycling construction and maintenance.

(Cochran, 2006) suggests that policy for recycling can be categorized in to three aspects, namely direct regulation, incentives and regulation. In this research the questionnaire developed include all the three aspects of policy statements that can be applied or guide asphalt pavement recycling. However, regulatory and incentives are given more attention in this study as they were considered important in developing the initial draft policy framework.

6.2 Questionnaire analysis

A questionnaire was developed and the responses analysed about developing a policy for asphalt pavement recycling. Design of the questionnaire was based on the information gleaned from the literature review (Cochran, 2006). Accordingly, 15 questions were prepared. It included open ended, choice types in the form of "Yes" or "No" and rating of option questions. Since this an issue policy, the questionnaire was sent out to experienced professionals, Directors, company manager and team leaders in the industry. Accordingly, 30 questionnaires were distributed and 24 responses were obtained. All the responses were encoded to spread sheet and analysis is made and presented. Accordingly, 92% of respondents agreed that a policy framework is required. It is

generally agreed by respondents that asphalt pavement recycling is attractive to developing countries but can be applied on major roads only. The responses showed that asphalt pavement recycling can improve the environment and contribute to good road asset management. The reasons recycling is not implemented on a wider scale in Ethiopia may be numerous. The questionnaire response and the factors affecting the implementation are shown in Figure 6-1.

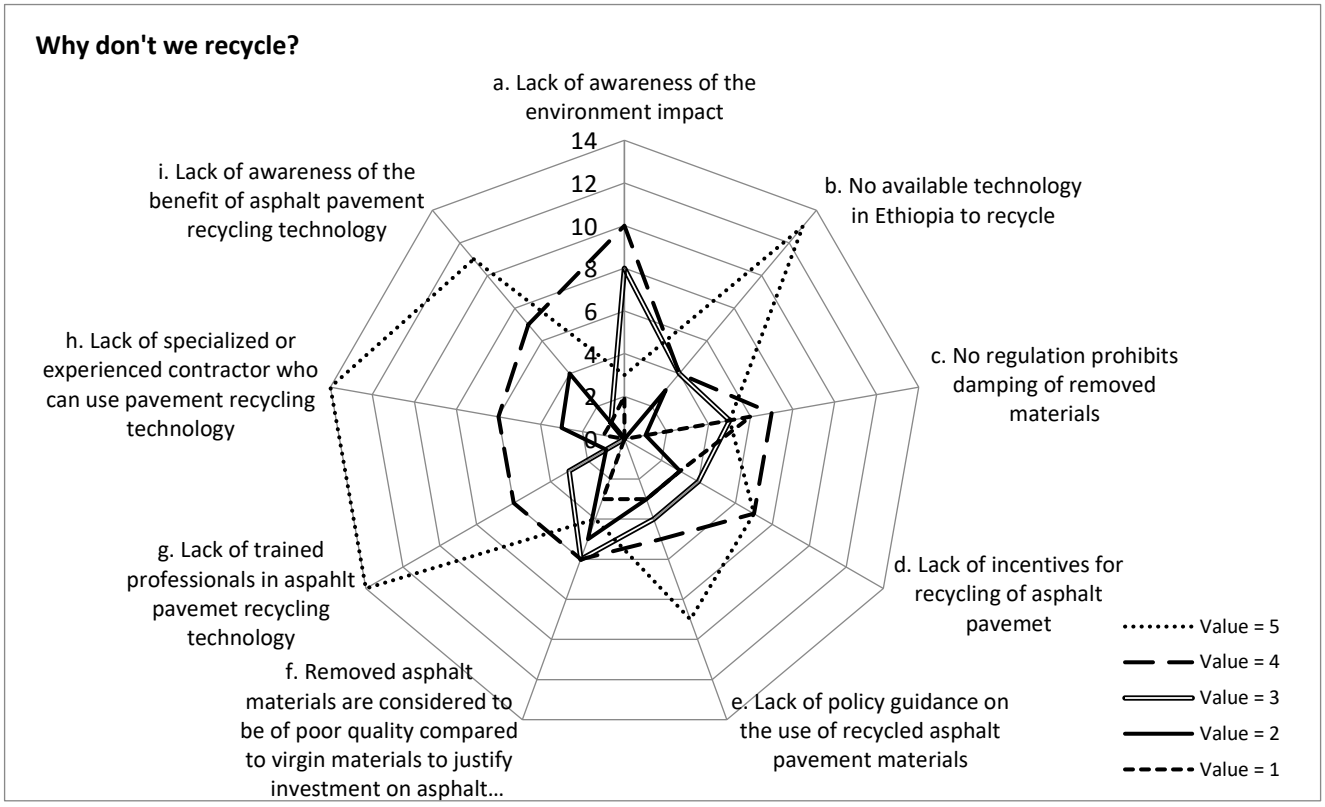
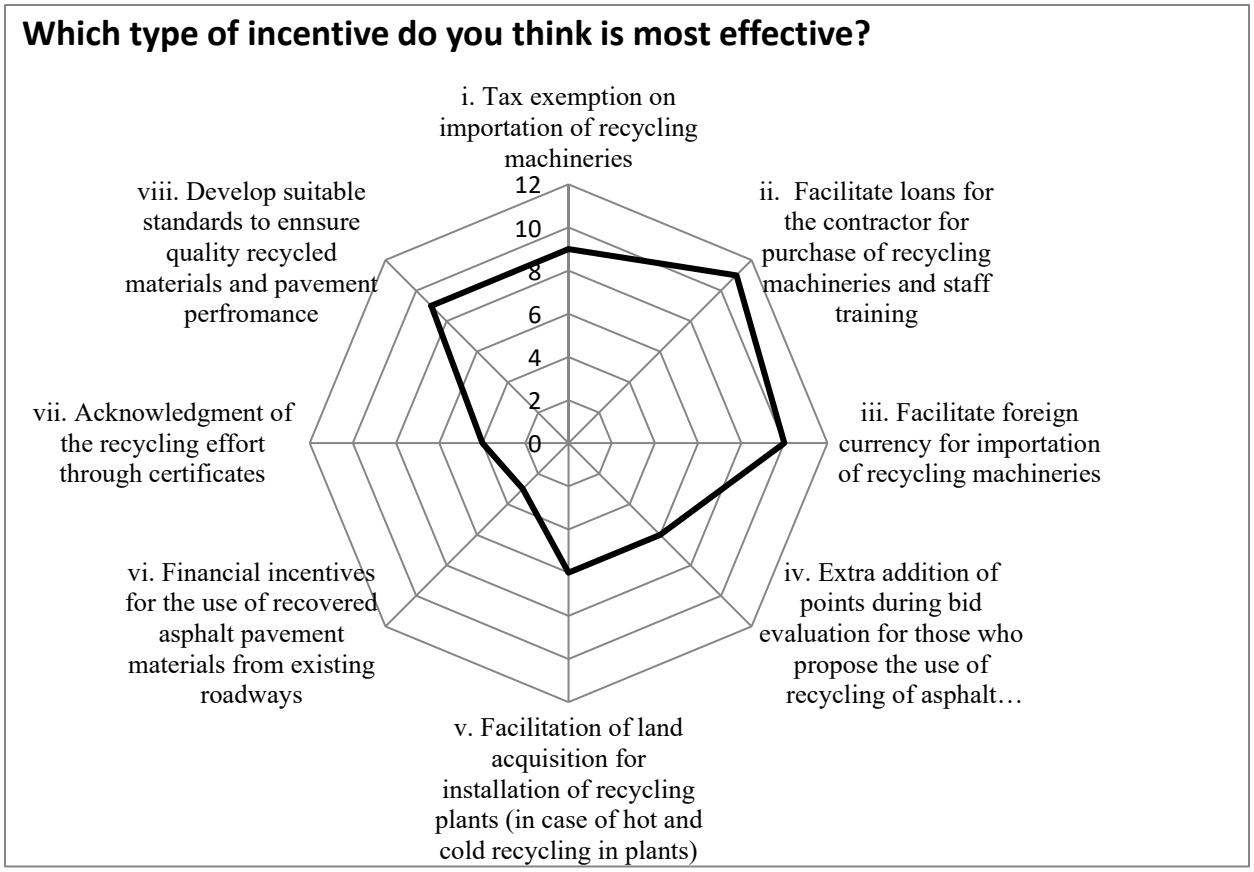


Figure 6-1 Questionnaire responses regarding factors for not recycling

The lack of a policy is not taken as a serious hindrance factor, rather the lack of specialised or experienced contractors and professionals who can implement the recycling, and the unavailability of the required technology are considered to be mainly responsible. It is also believed that there should be an incentive mechanism for contractors to recycle. Types or forms of incentives may vary and which incentive is most attractive to them (in Ethiopia) was assessed. Accordingly, loan facilitation for equipment purchase is the most attractive; while hard currency provision, tax exemption on equipment importation, and development of standards and specifications are considered also as incentives, as shown in Figure 6-2.

Currently, about 50% of the asphalt in roads can be recycled according to 38% of respondents; while 21% suggested 100% can be recycled, and 17% of respondents suggested 10% can be recycled. However, the concern that 100% recycling may not be achievable at the beginning is due to the lack of industry experience, and thus it is better to start with a lower percentage of



recycling.

Figure 6-2 Questionnaire responses regarding incentives

In conclusion, the result of the questionnaire analysis shows that asphalt pavement recycling needs to be supported by a policy framework and incentives should be put in place to develop interest in recycling RAP.

Considering the requirement of policy guidance and support for the implantation of asphalt pavement recycling 92% of the respondents have agreed that there should be a policy framework as shown in Figure 6-2.

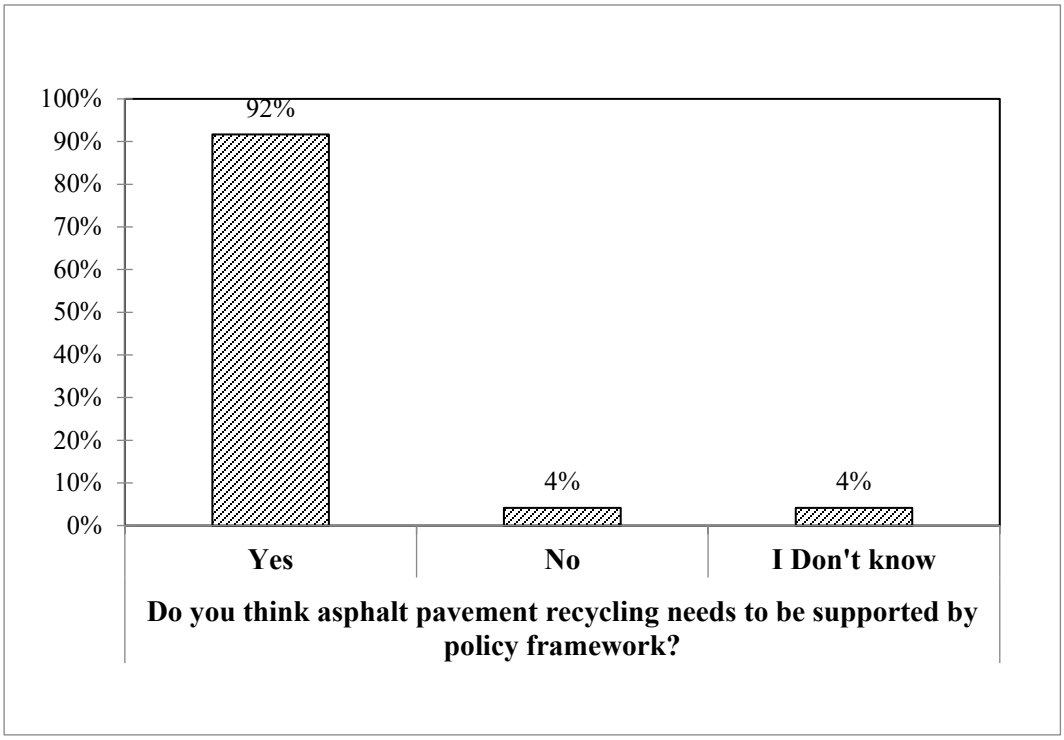


Figure 6-3 Response about the need for policy framework

6.3 Suggested policy statement

It is understood from the experience and knowledge of asphalt pavement recycling in developed countries that 100% of asphalt can be recycled and this can be done repeatedly. By discarding this precious material, very good quality aggregate is being wasted, along with time needed for construction and the money spent, all while the environment is being significantly abused. Therefore, it is time to encourage public and private contractors to recycle asphalt pavements through incentives and penalty schemes. Based on the questionnaire analysis results, statements that can be used as a policy guide were clearly visible and, thus, are formulated as shown below. These suggested policy statements need to be approved by a responsible government body so that it will be exercised uniformly in the road sector.

These policy statements are based on the questionnaire analysis results and the systematic review of asphalt pavement recycling carried out in this research project.

i. Asphalt pavement recycling would benefit industry and our environment through cost saving, minimised use of virgin materials, reduced GHG emissions, and cutting energy demand.
ii. On road rehabilitation projects, a minimum of 50% of the existing asphalt pavement material could go back to the road, either in the lower layers or on surfacing as the design suggests; while the rest can be taken to a central processing location.
iii. On each asphalt pavement rehabilitation project, a central RAP processing space could be prepared along the asphalt plant or crushing sites or both. This could be incorporated in the contract agreement.
iv. Contractor selection criteria may include use of recycled materials, including RAP and minimising environmental impact, amongst other factors.
v. Asphalt pavement recycling could be a priority option in the design of rehabilitation projects and selected new-build road categories.
vi. The government, through an implementing organisation, may provide training and an awareness program for asphalt pavement recycling.
vii. The government could facilitate and encourage investors interested in asphalt pavement recycling.
viii. A penalty could be applied to contractors or public bodies for dumping asphalt removed from road pavement on the sides of roads or to any form of landfill.
ix. The government would provide support for importation of recycling machines and accessories through hard currency facilitation and tax exemption.
x. The Federal Roads Authority could lead asphalt recycling initiatives through preparation of guidelines and standards for implementation.
xi. Research and trials are encouraged to maximise recycling and increase innovation for implementation of asphalt pavement recycling.
xii. Construction and rehabilitation projects may accommodate trial sections to prove new technologies for RAP, whenever needed by the implementing organisation.

7 DISCUSSIONS

7.1 Introduction

Recycling of asphalt road pavements is becoming a necessity in the rehabilitation of deteriorated pavements as raw materials used in their construction are becoming scarcer and more expensive. Increasingly, in road construction and maintenance its environmental impact has to be considered and thus recycling of existing asphalt pavement is believed to give significant cost savings in resources and minimises the negative impacts on the environmental (Weidong Cao, 2019). Economic analysis conducted on the use of reclaimed asphalt pavement (RAP) materials has also indicated that their use in large quantities is cheaper compared to the use of virgin materials.

7.2 Economic analysis

A systematic review of the literature concerning asphalt pavement recycling (ARRA, 2001) (Kandhal, 1997) (Zaumanis, 2014) (Tang, 2012) (Al-Qadi, 2007) (NCHRP, 2011) (Lee, 2014) (Hope, 2015) (Horvath, 2004)) showed that recycling was a cost saving exercise. Although the cost saving depends on the amount of percentage of RAP used. In general, cost savings increase as the RAP amount increases (Ksaibati, 2015) (Mantalovas, 2019) (Magar, 2022) (Farina, 2017). The literature also informs that asphalt pavement can be 100% recycled, which makes it highly cost effective (EAPA, 2017) (Esenwa, 2013) (Zaumanis, 2016) (Zaumanis, 2014). In this research also it has been shown that the highest cost benefit is obtained for the higher RAP proportion in the new mix. A life cycle cost analysis is necessary to determine the long term economic and technical performance of using RAP. The savings arising from using RAP for a road agency can be critical in their decision making.

7.2.1 Economic indicators

The net present value (NPV) is calculated to assess the difference between the present value of cash inflows and the present value of cash out flows over a period of time. Future streams of payments are calculated at 12% discount rate for all the combinations of new and RAP containing mixes. The highest NPV was registered for 90% RAP in the new mix for all three climate conditions. A tropical humid climate has the highest NPV, while the semi-arid climate

shows low NPV values in all combinations of RAP containing mixes. Analysis made using the HDM4 has shown that the NPV for all combinations of RAP in a new mix have an increasing cost benefit trend compared to asphalt without RAP.

Although, the NPV values are all positive, the benefit/cost analysis indicated that only 70% and 90% RAP have benefit/cost ratio value greater than one. Theoretically, a value of the benefit/cost ratio of less than one indicates that the cost outweighs the benefits, suggesting that the alternative shall not be considered. However, based on other indirect benefits such as a reduction in environmental damages, and a reduced landfill use for waste disposal, it is considered that it is still beneficial to recycle asphalt pavements. Recycling of asphalt pavement can give a reduction of CO^2eq by 35% compared to asphalt made with virgin materials (Zaumanis, 2014). Due to the reduced hauling of virgin materials the air quality is improved, energy is conserved, natural resources are reserved as a result of the reduced use of new materials (Kandhal, 1997).

It is also to be noted that benefit/cost undermines the many factors that affect a project's viability, the rule that a value less than one is not a failure of that alternative may be misleading. The cost/benefit of the alternatives in this research considered routine maintenance and overlay costs of a road section constructed with HMA mixes containing RAP materials. These costs remain constant for the three different climatic conditions, semi-arid, sub-humid and tropical humid, considered in the evaluation. Considering the viability of using RAP solely on the benefit/cost ratio would not be satisfactory, as it does not give a complete picture, the standard calculation excludes indirect, but significant benefits. Therefore, in view of the positive NPV, and the indirect benefit that can be obtained, it is thought that all percentages of RAP will be beneficial and can be considered for use.

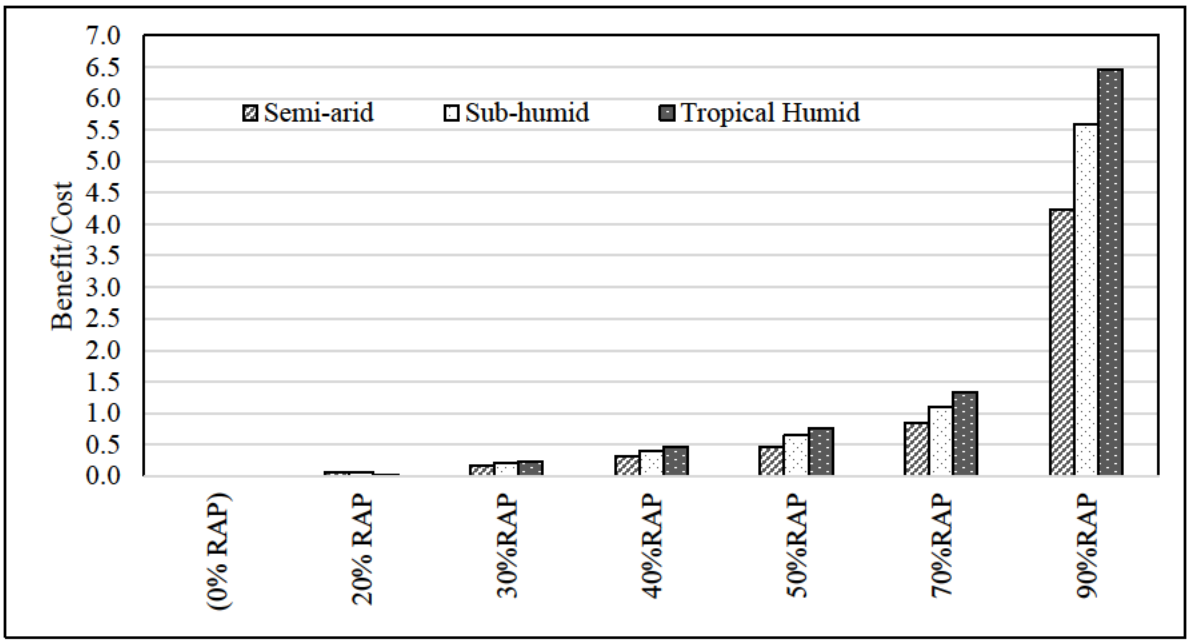


Figure 7-1 Cost/Benefit of RAP for semi-arid, sub-humid and tropical humid climates

7.2.2 Life Cycle Cost Analysis (LCCA)

A LCCA was carried out for all the RAP mix proportion of asphalt mix and the control mix to investigate the economic benefits that can be obtained (using RAP). The economic benefit was evaluated in terms of life-cycle cost of each mix proportion. All input data and calibration parameters were relevant to the location from where the test samples were collected, so as to reflect the real scenario of pavement performance and economic situation in order to obtain realistic results of the analysis. The economic analysis was based on the NPV to evaluate and compare the benefit of each mix containing the RAP material. Asphalt concrete pavements are designed for a design life of 15–20 years depending on the traffic level expected to use the pavement. In this research, 20 years of analysis is chosen, considering that proper routine maintenance and overlays will be periodically applied on the pavement so that the HMA constructed pavement will serve the maximum design life. Accordingly, rutting and roughness (IRI) were used to evaluate the performance of RAP in the analysis period of 20 years.

In the LCCA the input data is sometimes incomplete so that their estimated values are used (Farina, 2017). In this study, whilst some data had to be estimated, all available data obtained from ERA (road condition data, traffic data, road maintenance costs, vehicle fleet data, road

design parameters) were used. The results of the LCCA carried out using HDM-4 are compatible with the works of other researchers (Sharmeny Mhlongo, 2014; Yaning Qiao, 2019; Waqas Rafiq, 2021) and show that as RAP material proportions are increased the NPV also increases. Asphalt without RAP was used as a control for comparison and the analysis showed that the NPV increased by 112% for the 90% RAP proportion.

It was found that the road user cost increased significantly for the higher proportions of RAP; whilst the agency cost decreased markedly. The literature (Andreen, et al., 2012) (Zaumanis, 2014) also indicated that as the proportion of RAP increased, cost saving in terms of asphalt also increased. In the literature review section 3.11.1 Figure 3-9 showed that research shows (Hope, 2015) (Andreen, et al., 2011) (Zaumanis, 2014) the increase in cost savings per unit cost of asphalt for different proportions of RAP. This study has also confirmed that there is a significant cost saving based on the economic analysis result using HDM-4 as shown in Figure 7-2. Though the cost saving is lower than obtained by other researchers the saving trend is similar and increasing with the increase of RAP content in the mix. Figure 7-2 is plotted along with the data from the other researchers to show the similarity and comparison purposes. Since asphalt is the most expensive component of the mix, the savings made using RAP may have a significant effect on the project which is translated to agency cost.

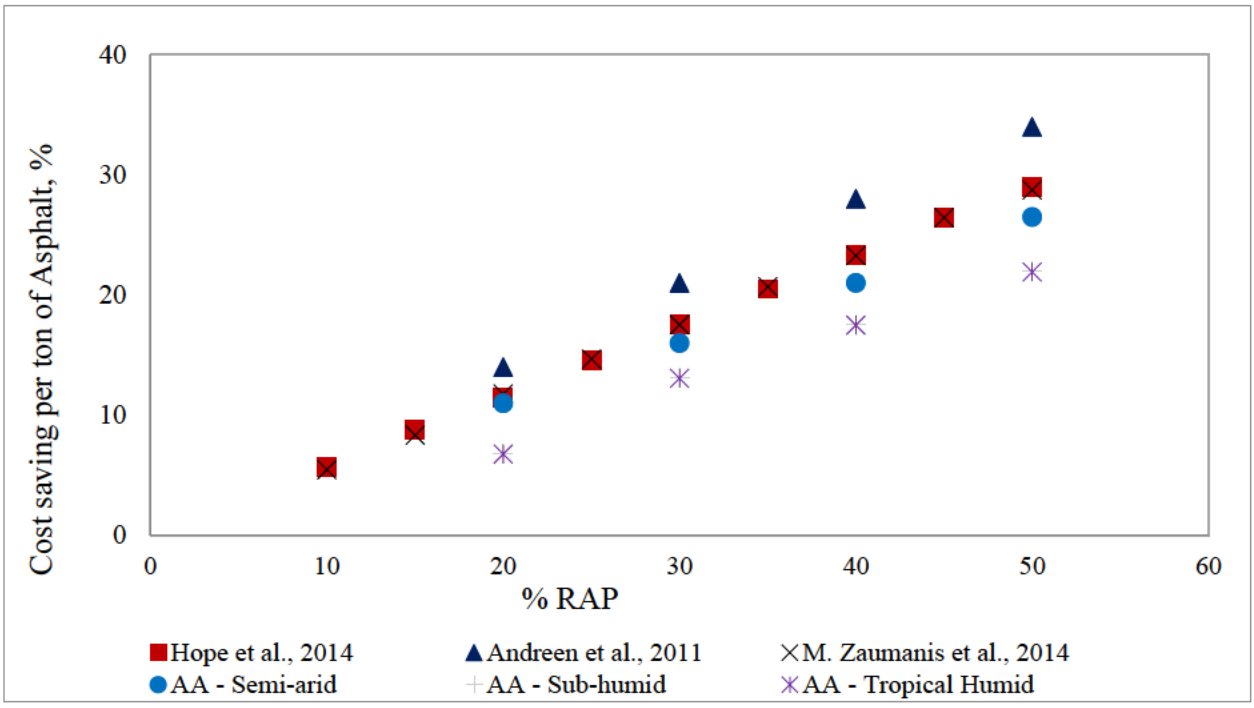


Figure 7-2 Relationship of RAP content and cost saving

The road agency cost decreased significantly as the proportion of RAP increased, as shown in Figures 7-3 and 7-4 for costs in Ethiopia, in terms of Ethiopian Birr (ETB). Agency cost has major components for virgin mix preparation, such as quarrying and crushing of crushed stone for the asphalt mix and bitumen purchase and transportation. The cost of the asphalt mix plant operation will be the same for production, and the savings by using the RAP material are mainly due to reductions in quarrying and crushing of virgin aggregate, and the amount of bitumen used. As these operations are similar irrespective of the climate conditions, the savings for the three conditions considered in this research, semi-arid, sub-humid and tropical-humid, are similar.

Table 7-1 Discounted Agency costs and cost savings

	Discounted Agency costs			**Cost saving compared to Base case (No RAP)**		
Alternatives	**Semi-arid**	**Sub-humid**	**Tropical Humid**	**Semi-arid**	**Sub-humid**	**Tropical Humid**
0% (Base Case)	534.4	536.4	538.8	0.0	0.0	2.4
20%	477.6	479.7	482.1	56.7	56.7	59.1
30%	449.3	451.3	453.7	85.1	85.1	87.5
40%	420.9	423.0	425.3	113.5	113.5	115.9
50%	392.5	394.6	397.0	141.9	141.9	144.2
70%	328.9	330.6	332.4	205.5	205.9	208.3
90%	272.1	273.8	275.6	262.3	262.6	265.0

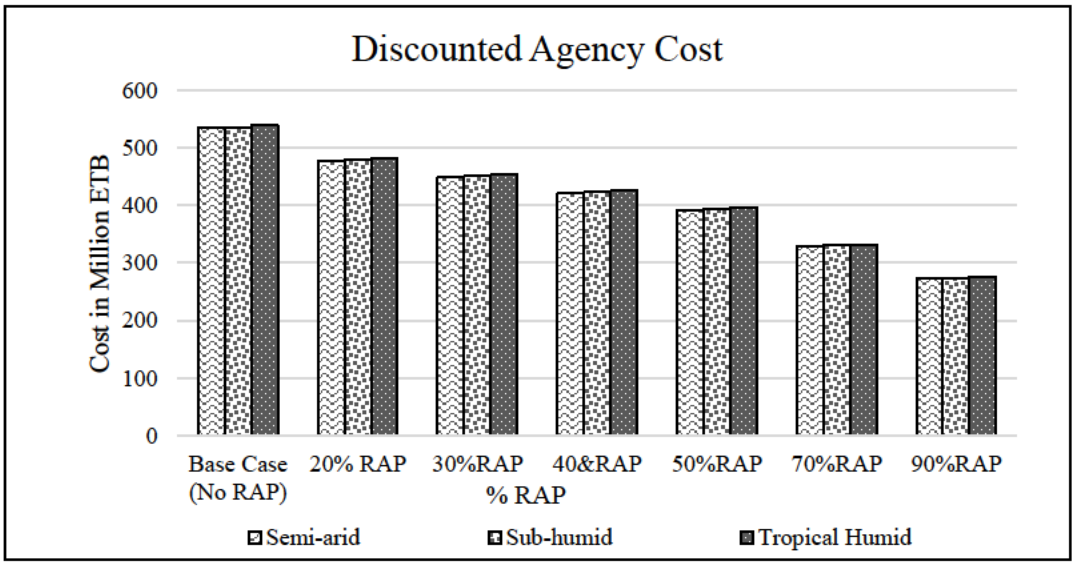


Figure 7-3 Discounted Road agency cost and RAP content

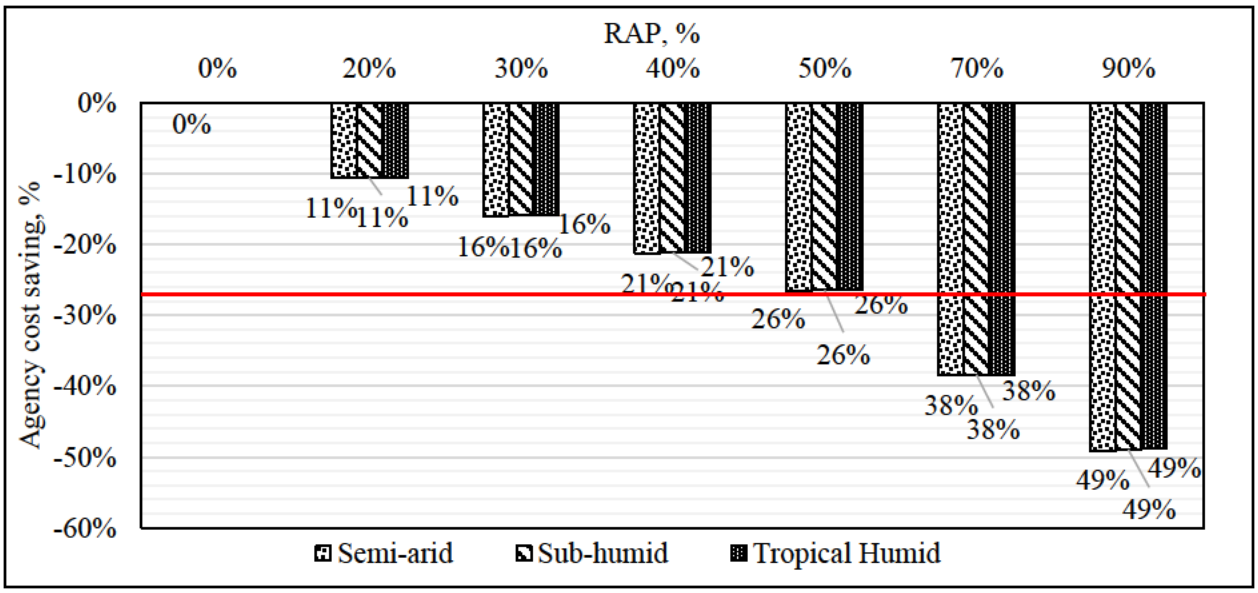


Figure 7-4 Agency cost savings

Overall, use of recycled materials in the base and sub-base has a potential life-cycle cost savings of 21%, while providing a longer service life (Edil, et al., 2010). It is also indicated that cold-mix recycling can result in a total expenditure of 40 to 50% less compared to the conventional method (Kandhal, 1997). From this research it is found that using 90%RAP in the new mix will give 49% cost savings compared to using virgin materials, which is very significant. The maximum cost saving of 49% is obtained for a semi-arid climate at 90% RAP usage. The cost saving obtained in the sub-humid and tropical-humid climate by using 90% RAP is 40% in both cases.

The average cost savings for the three climates by using 20% to 90% RAP is 27% for all three climate zones. Figure 7-4 shows that the minimum cost saving is for 20% RAP usage where the cost saving obtained was 11% for semi-arid, 7%. Therefore, we can generalise that an average of 27% cost saving can be obtained on agency costs by using 20% to 90% RAP. This is a significant cost saving for a developing economy like the case of Ethiopia, where the gap in providing basic access and maintenance of paved road network is challenged by the allocation of insufficient budget.

The most significant cost saving was obtained on the agency cost. As the cost saving on other parameters, VOC and road user costs are not affected as a result of using RAP in mixes and stays

similar to the base case. This is due to the increased performance of the pavement and the deterioration that directly affects these parameters is similar to the base case.

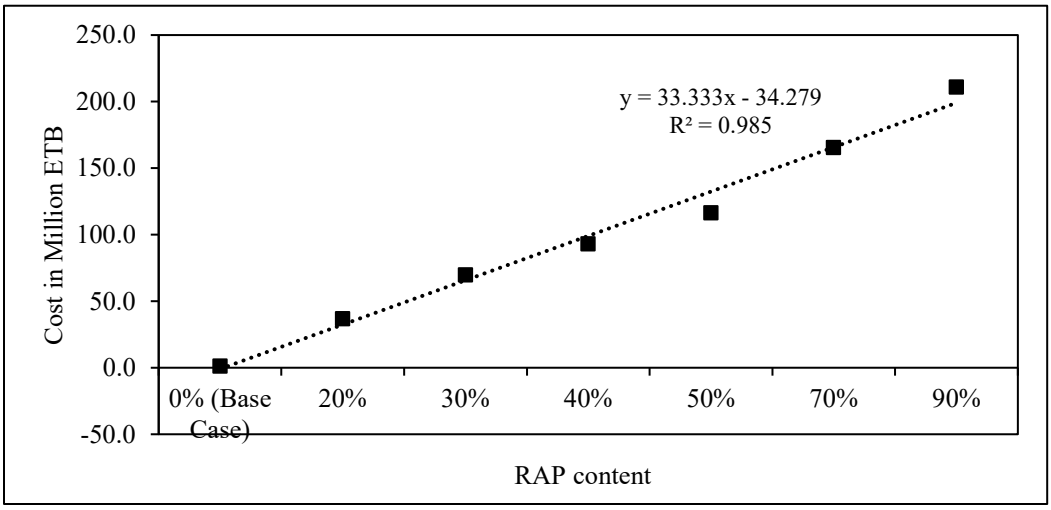


Figure 7-5 Cost saving for semi-arid climate

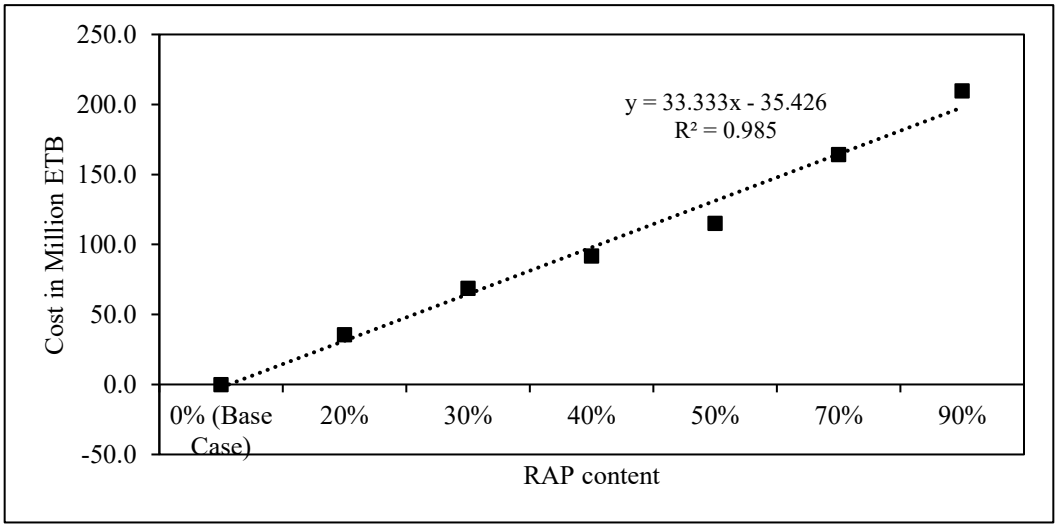


Figure 7-6 Cost saving for sub-humid climate

The LCCA shows that asphalt pavement recycling in all the three climate types provides significant savings, as seen in Tables 7-2 to 7-4

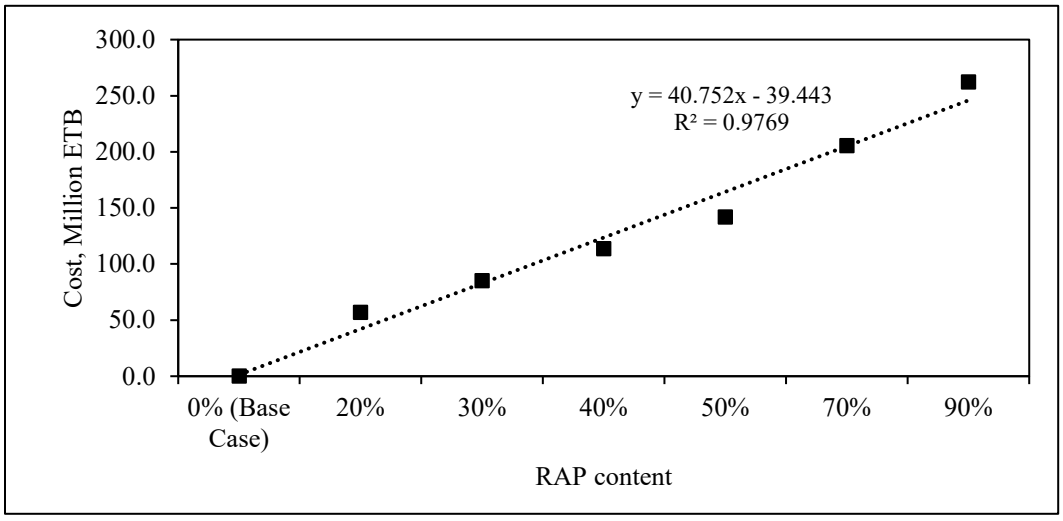


Figure 7-7 Cost saving for tropical-humid climate

Table 7-2 Discounted life cycle cost for semi-arid climate in ETB million

Semi-arid	Recurrent costs	Capital costs	Agency costs	VOCs (semi-arid)	Travel time costs	Accident costs	Road User Costs	Total transport costs
Base Alternative	88.6	445.8	534.4	64833.0	5460.7	121.5	70415.2	70949.6
20% RAP	88.6	389.0	477.6	64863.5	5460.9	121.5	70445.9	70923.5
30% RAP	88.6	360.7	449.3	64854.9	5460.9	121.5	70437.3	70886.6
40% RAP	88.6	332.3	420.9	64844.1	5460.8	121.5	70426.5	70847.4
50% RAP	88.6	303.9	392.5	64832.1	5460.8	121.5	70414.4	70806.9
70% RAP	81.7	247.2	328.9	64828.8	5460.8	121.5	70411.1	70740.0
90% RAP	81.7	190.5	272.1	64296.0	5455.6	121.5	69873.1	70145.2

Table 7-3 Discounted life cycle cost for sub-humid climate in ETB million

Sub-humid	Recurrent costs	Capital costs	Agency costs	VOCs (sub-humid)	Travel time costs	Accident costs	Road User Costs	Total transport costs
Base Alternative	90.7	445.8	536.4	65736.4	5470.4	121.5	71328.3	71864.7
20% RAP	90.7	389.0	479.7	65773.4	5470.8	121.5	71365.8	71845.5
30% RAP	90.7	360.7	451.3	65745.2	5470.5	121.5	71333.2	71784.5
40% RAP	90.7	332.3	423.0	65715.1	5470.1	121.5	71306.7	71729.7
50% RAP	90.7	303.9	394.6	65683.0	5469.6	121.5	71274.1	71668.7
70% RAP	83.4	247.2	330.6	65670.3	5469.5	121.5	71261.3	71591.8
90% RAP	83.3	190.5	273.8	64942.0	5461.3	121.5	70524.8	70798.6

Table 7-4 Discounted life Cycle cost for tropical-humid climate in ETB million

Tropical -humid	Recurrent costs	Capital costs	Agency costs	VOCs (tropical-humid)	Travel time costs	Accident costs	Road User Costs	Total transport costs
Base Alternative	93.0	445.8	538.8	66283.6	5481.0	121.5	71886.1	72424.9
20% RAP	93.0	389.0	482.1	66330.4	5481.9	121.5	71933.8	72415.9
30% RAP	93.0	360.7	453.7	66288.1	5481.0	121.5	71890.6	72344.3
40% RAP	93.0	332.3	425.3	66242.5	5480.0	121.5	71844.1	72269.4
50% RAP	93.0	303.9	397.0	66194.2	5479.0	121.5	71794.7	72191.7
70% RAP	85.2	247.2	332.4	66162.1	5478.3	121.5	71761.9	72094.3
90% RAP	85.2	190.5	275.6	65331.5	5466.5	121.5	70919.5	71195.1

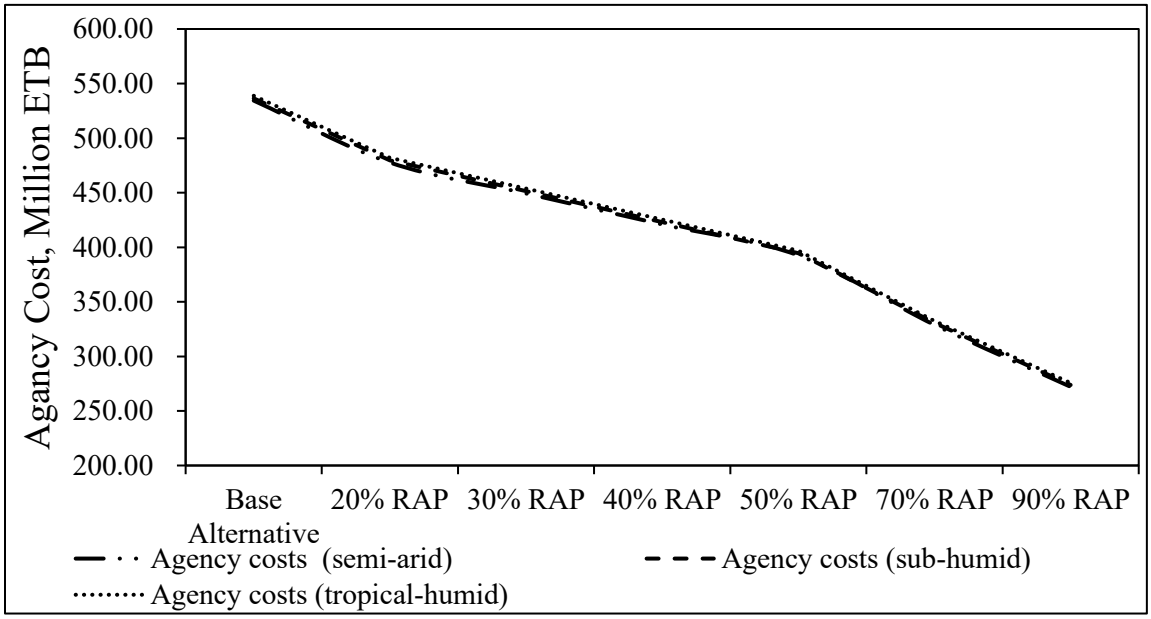


Figure 7-8 Agency Cost

Cost savings for sub humid and tropical humid climates have similar values and the maximum saving is obtained for 90% RAP. As shown in Figure 7-1, in all the three climates cost savings increased as the RAP content increased. This indicates that increasing the amount of reclaimed asphalt use in pavement rehabilitation increases benefits such as reduced road agency costs. Higher cost savings in a semi-arid climate means that Reclaimed Asphalt Pavement in a hot climate will perform better compared to a wet and cold climate. This suggests that in most of the sub-Saharan region, inclusion of RAP may be cost effective for pavement rehabilitation.

However, it should be noted that in all three climatic conditions asphalt pavement recycling proved to be cost-effective as indicated by the LCCA.

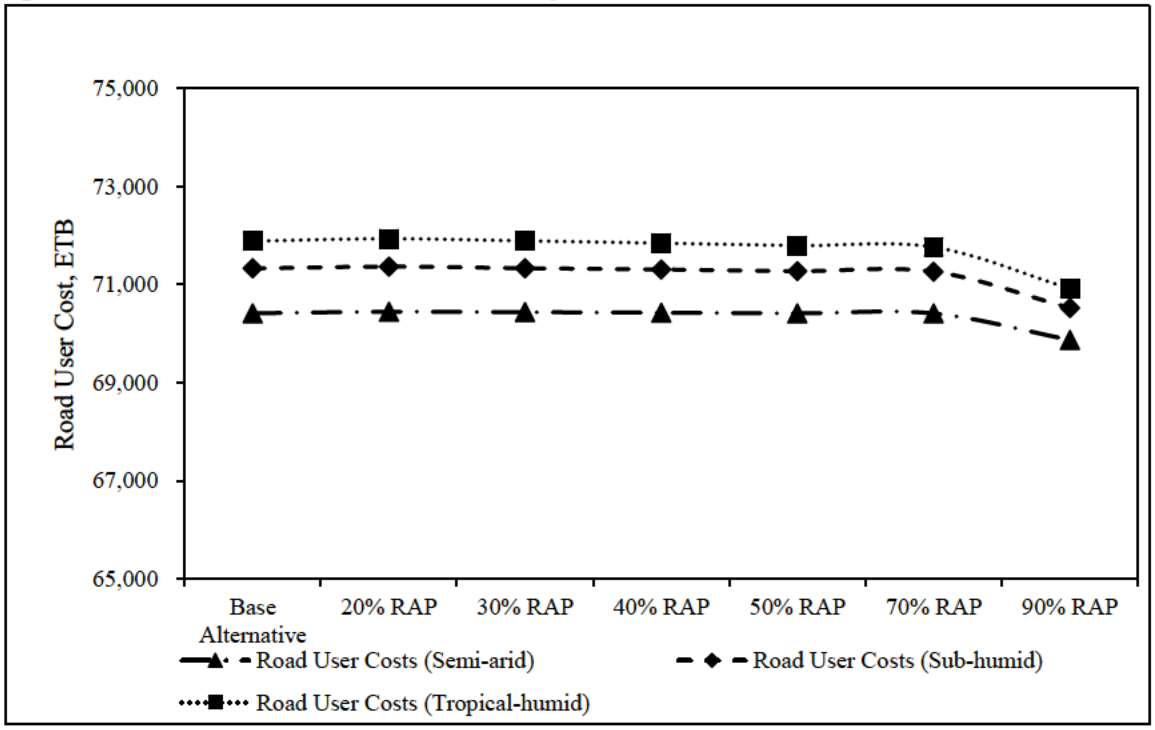


Figure 7-9 Road User Cost

7.2.3 Pavement performance

The performance of Reclaimed Asphalt Pavement gives an equal or better execution compared to a new mix (Kandhal, 1997). From the LCCA, it was noted that IRI values for the different RAP proportions in the mix indicate a similar performance to that new mix, except towards the end of the twenty-year analysis period where 90% and 70% RAP showed lower IRI values compared to asphalt made from virgin materials. This also justifies that with the increasing RAP content the base alternative showed higher IRI values towards the end of the analysis period.

A higher RAP percentage, however, showed higher cracking potential compared to the control mix. The cracks initiate at same time for all cases and 70% and 90% RAP showed the highest potential for cracking, whilst mixes with 30%, 40%, and 50% RAP showed lower predicted cracking compared to the control mix. It is conjectured that as the amount of RAP increases, the aging of RAP and increased fines in the asphalt may lead to earlier onset of cracking (Kandhal, 1997). Proper gradation and rejuvenation of old bitumen may reduce crack susceptibility asphalt.

Rutting in all combinations of RAP and new mixes shows similar behaviour. Its progression through time is also not significant, as the slope of the curve in Figure 7-12 indicated. This is one of the justifications that RAP materials perform equally or better compared to new mixes. One of main problems on a road pavement is rutting, which results from asphalt mixes, and the use of RAP materials does not have a different rutting potential from the new mix. If that is the case, using RAP material will contribute to environmental degradation by reducing exploration of new materials, crushed aggregate and bitumen. A semi-arid climate is more suitable for asphalt pavement recycling both in terms of economic and pavement performance. Lower values of rut depth, IRI and structural cracks are seen for a semi-arid climate, while the highest values are recorded for a tropical humid climate.

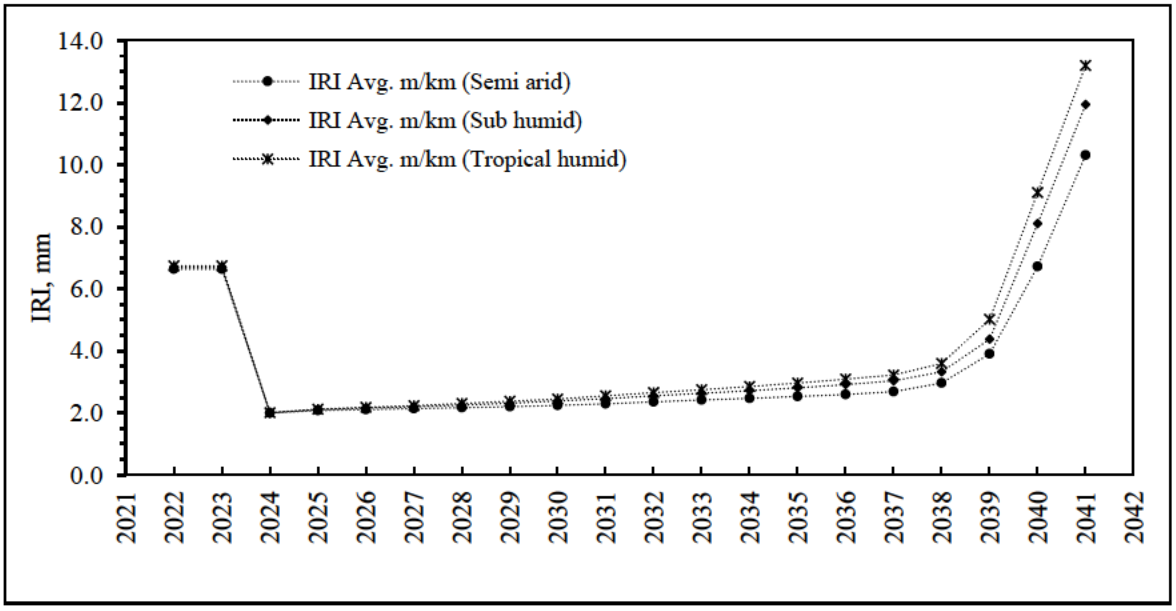


Figure 7-10 Predicted change in IRI for different climates

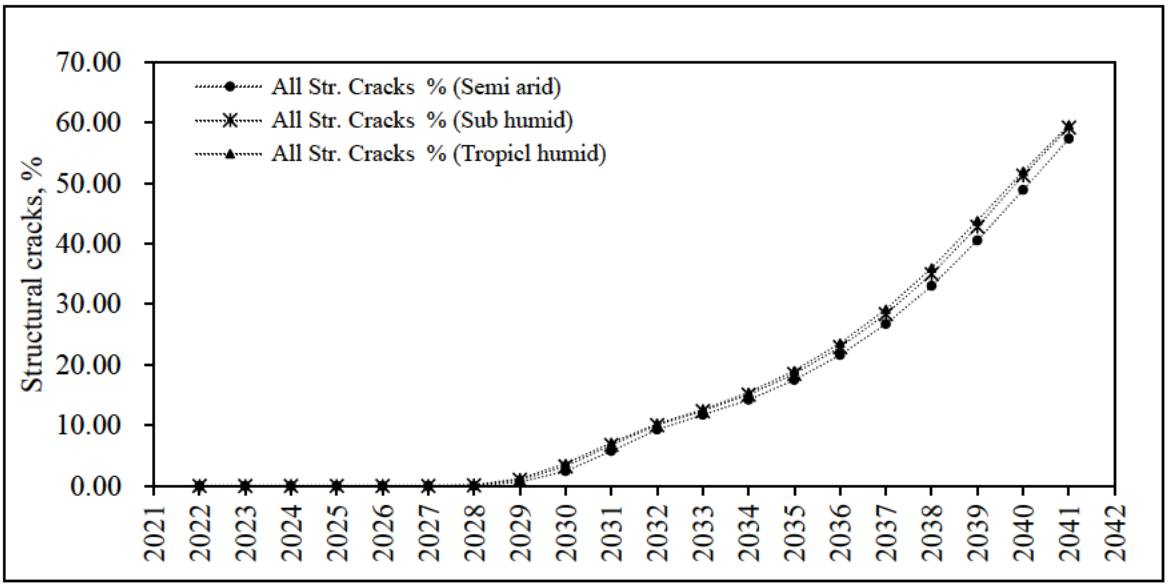


Figure 7-11 Predicted change in cracks for different climates

This study has shown that based on both economic and pavement performance parameters, RAP may be more suited for pavement rehabilitation in hot compared to cold climates. Most of sub-Saharan Africa, which incorporates some of the poorest countries, has a hot climate and may be well suited to using RAP for asphalt pavements' rehabilitation on the grounds of both the reduced cost and environmental impact. Although Ethiopia has both hot and cold regions, rehabilitation in hot regions and future road rehabilitation schemes will include consideration of the use of RAP for rehabilitation in hot regions as a result of this study. Clearly, further laboratory and field investigations will be required, before incorporating the use of RAP in Ethiopian Roads Standards.

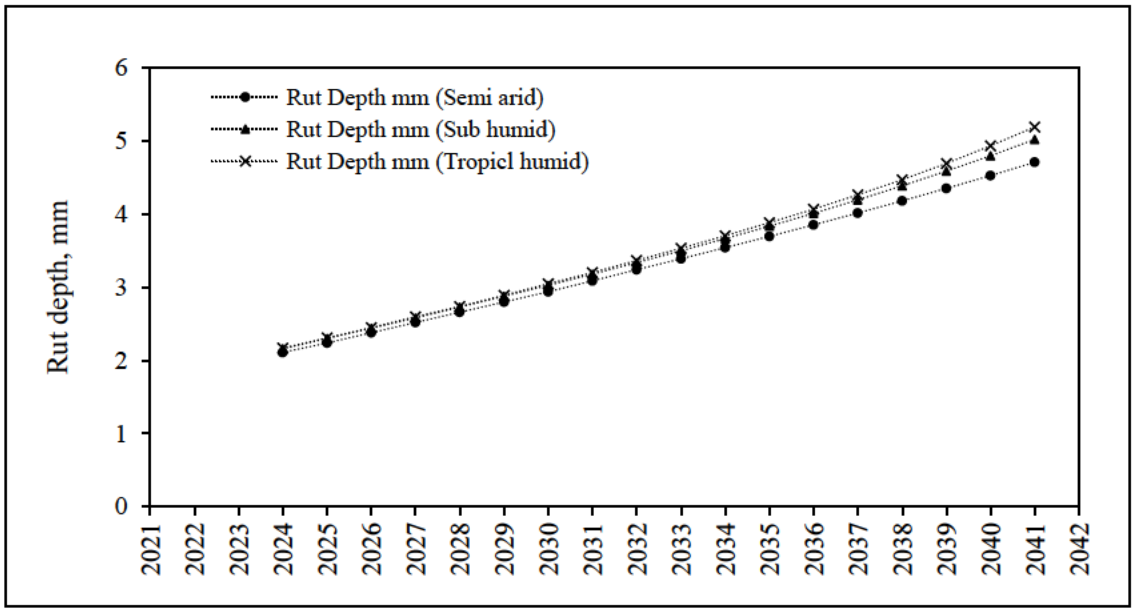


Figure 7-12 Predicted pavement rutting for different climates

7.3 Laboratory experiment results

Pavement performance problems such as rutting, cracking and potholes are frequently happening and lead to a high degree of roughness and increased maintenance and rehabilitation works. Recycling of existing pavement will significantly reduce maintenance and rehabilitation costs; however, it is also important to see how RAP materials behave in terms of rutting and cracking of pavements compared to new mixes before a decision is made to recycle existing pavement. Limitations of RAP materials in the use of new mixes need to be given attention as they may cause undesirable effects such as cracking after pavement construction. The main limitations or influencing factors that need attention are (Zaumanis, 2014) (Wirtgen, 2012):

- Properties of aged bitumen in the RAP that may cause cracking,
- Composition and uniformity of existing asphalt material,
- The temperature of the asphalt in the milled horizon,
- Degree of blending and diffusion that occurs between the virgin and RAP binder, and
- RAP aggregate properties especially the fine contents.

The nature and grading of RAP material depends on the nature and thickness of the existing pavement to be recycled (Earland, 1999). The source of RAP for this research is a single source from the top layer of the existing pavement, so the variability due to RAP collected from

different sources is avoided. The particle size distribution of the RAP materials used fits within the grading curve for a surfacing course specification and this is expected as the RAP was collected from the surface layer. Therefore, the new mixes containing RAP materials were prepared and tests were conducted accordingly. A totally new mix was prepared and tested and the results were established as a reference for the RAP containing mixes.

Paucity of literature on RAP from the sub-Saharan countries suggest asphalt pavement recycling is not very common in the region. On the other hand, current high prices and scarcity of input materials for new asphalt, such as bitumen and crushed stone, are negatively impacting the maintenance and rehabilitation of pavements. Moreover, scarcity of these materials is also becoming a serious problem more frequently. Therefore, wasting existing asphalt during rehabilitation is considered as wasting high quality aggregates and also damaging the environment by using land for disposing of it. Instead, using the reclaimed asphalt pavement material will mitigate the three most important current problems, cost of rehabilitation, energy requirement and environmental impact.

Overloading, of heavy trucks on the trunk road networks is very high and largely contributes to fast deterioration of pavements. Based on the Ethiopian Roads Authority annual report for 2001 – 2022 on axle load control activities, overloading in terms of the number of vehicles was over 39% (out of the weighed 139,187 trucks). With this situation the maintenance and rehabilitation need is very high and material requirements have also increased. Thus, the need to reuse such expensive materials, bitumen and crushed aggregate, is very important.

The use of RAP materials at high percentages is encouraged, as the economic analysis indicated that more economic advantages are obtained as RAP percentages are increased. Therefore, it is good to use more RAP materials and this can be done with good RAP management practices, modern production technologies and advanced knowledge of mix design (Mallick, 2015). The current average RAP use in HMA is between 10% and 20% (Copland, 2011) and more information can easily be found for this category, thus, in this research it is desirable to investigate the use of higher proportions of RAP. There is limited information so far on their use and performance and so accordingly, from 20% - 90% RAP content was selected for this study.

7.3.1 Marshall test

7.3.1.1 Specific gravity and voids

The Marshall test results indicated the air voids and densities for different proportions of RAP in HMA mixes. Densities are useful to determine the basic HMA physical properties and the main density types used are the bulk specific gravity and theoretical maximum specific gravity. The values of these densities/specific gravity are influenced by the types and amounts of aggregates, asphalt binder, and other materials present in the mixtures. The bulk specific gravity is measured in dry conditions and at a saturated surface dry (SSD) condition and plotted against the RAP content. The theoretical maximum specific gravity is the specific gravity of a mix when the air voids are eliminated. The theoretical maximum specific gravity shall be greater than the bulk specific gravity and this is true in this study also, as shown in Figure 7-13.

As the RAP content was increased the bulk density also tended to increase gradually while the theoretical specific gravity decreased as seen in Figure 7-13. These trends were considered to be due to decreased air voids in the mix. The theoretical maximum Specific Gravity tended to decrease compared to the Bulk Specific Gravity.

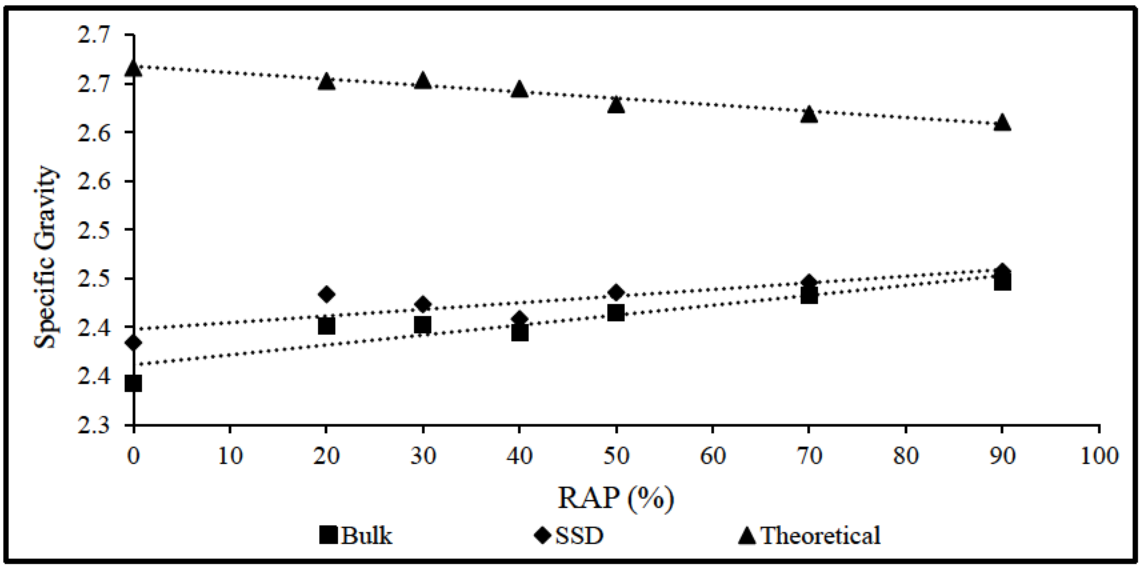


Figure 7-13 Density vs RAP content

Percent of air voids in the total mix decreased with the increase in the RAP content. Voids in the mineral aggregate (VMA) also show a decreasing trend as expected. The RAP aggregates are

coated with bitumen and the voids in the mineral aggregates are filled with bitumen. Therefore, it is expected that the VMA will show a decreasing trend. Likewise, it is expected that the voids filled with bitumen (VFA) will also increase with the increase in the RAP material for the same reason that bitumen used in the existing RAP material causes the amount of bitumen to increase. Therefore, the voids in the mix decrease as the amount of binder increases due to the existing bitumen in the RAP and decreasing voids in the mineral aggregate as RAP percentage increases. This is shown in Figure 7-14.

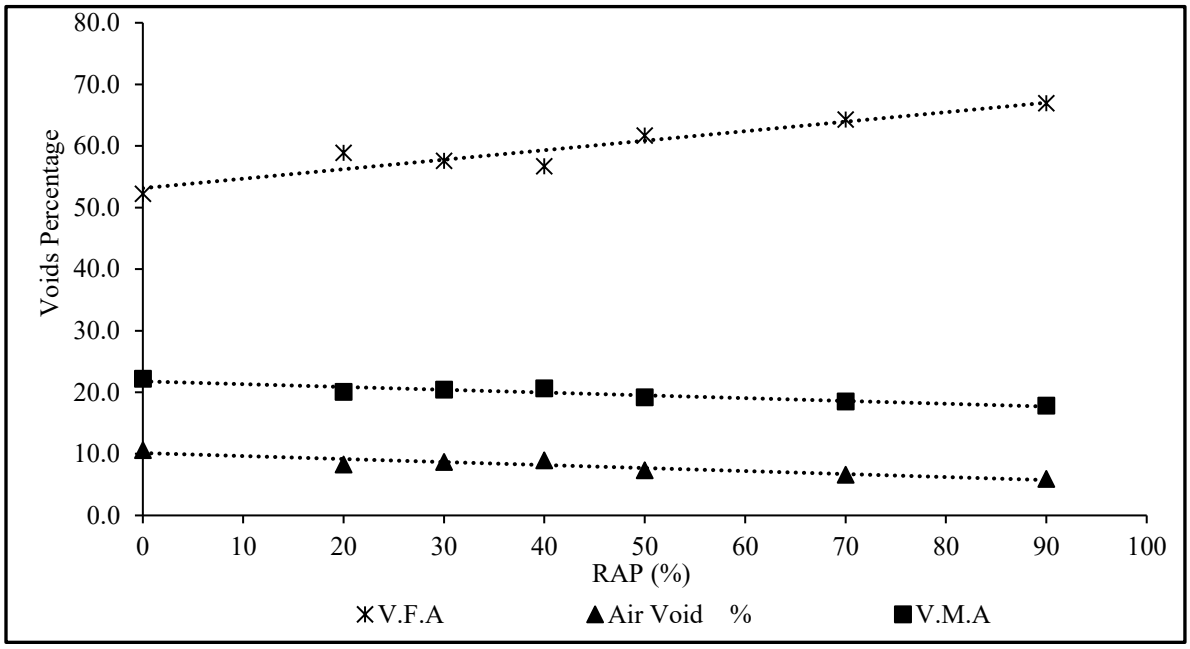


Figure 7-14 VMA, VMF and Air Voids

7.3.1.2 Flow and stability

Tests were conducted based on the Marshall test method, as indicated in the ERA specification (Ethiopian Roads Authority, 2013) and shown in Table 7-5. For an AC wearing course values for a high traffic level and for a pure HMA mix, are stability 8 KN and flow 2 to 3.5 mm. The test results on samples of the base case (no RAP) mix give stability 6.6 KN and flow 2.13 mm. The flow value satisfies the specification requirement for a high traffic level, while the stability does not. Both stability and flow values, however, satisfied the requirements for a medium traffic level, for which the specification for stability is 5.3 KN and flow is 2 to 4 mm. Therefore, it can be established that the base case (no RAP) mix satisfied all requirements for the medium traffic

level and mixes containing RAP material were evaluated and compared to the base case (no RAP) mix accordingly for medium traffic.

The 20% RAP content mix had a stability of 5.08 KN and flow of 3.85 mm and indicates that the stability requirement does not satisfy the minimum requirement (5.3 KN) for medium traffic (Ethiopian Roads Authority, 2013). The rest of the mixes, 30%, 40%, 50%, 70%, and 90% RAP mixes satisfy the requirements. At 50% RAP, although the values are higher than the base case (no RAP) mix it still showed lower stability and high flow compared to 30% and 40% RAP contents.

Table 7-5 summarizes the stability and flow results and specification requirements.

Specification for AC wearing course up to 5Million ESA			**RAP %**	**Stability (KN)**	**Flow (mm)**
	Min. Stability (KN)	**Flow (mm)**	**0**	6.60	2.13
			20	5.08	3.85
Heavy traffic (1-5million ESA)	8.0	2 – 3.5	**30**	9.35	2.98
Medium Traffic (0.4-1million ESA)	5.3	2 – 4.0	**40**	7.48	2.30
			50	9.11	3.05
			70	9.91	2.55
Light Traffic (<0.4million ESA)	3.3	2 – 4.5	**90**	11.32	1.93

Generally, mixes with RAP material of over 30% content give a better performance in terms of flow and stability for medium traffic levels; whereas, mixes with 50% and 70% RAP content satisfy the requirements of flow and stability for high traffic levels. The mix containing 90% RAP had a lower value of flow while showing the highest stability. It is noted that RAP materials in higher proportions give increased stability which also gives the mix an increased ability to resist loads and the results in this study confirm this.

However, lower or near the boundary minimum flow values of 2 mm, for a higher content of RAP, mean that the mix will be stiff and susceptible to cracking, (Yinning Zhang, 2016) (A K Arshad, 2017), or breakage. It requires adjustment in the amount of virgin bitumen or use of other agents to improve the flow properties. The literature indicated that adding rejuvenators will increase the fatigue resistance of the mixtures containing RAP (Zaumanis, 2014). Therefore, for higher RAP contents the performance can still be enhanced by using rejuvenating additives in the mix, which is even expected to deliver better results. Figures 7-15 and 7-16 show that the results of

stability and flow findings respectively, compared to other researchers (references) who have undertaken similar studies. The trends fond are similar. In general, the stability of mixes containing RAP materials increases as the RAP content is increased. The trend of the current finds and other researchers' (A K Arshad, 2017) (Waqas Rafiq, 2021) (Anon., n.d.) is similar for flow values :decreasing flow values with the increase of RAP content.

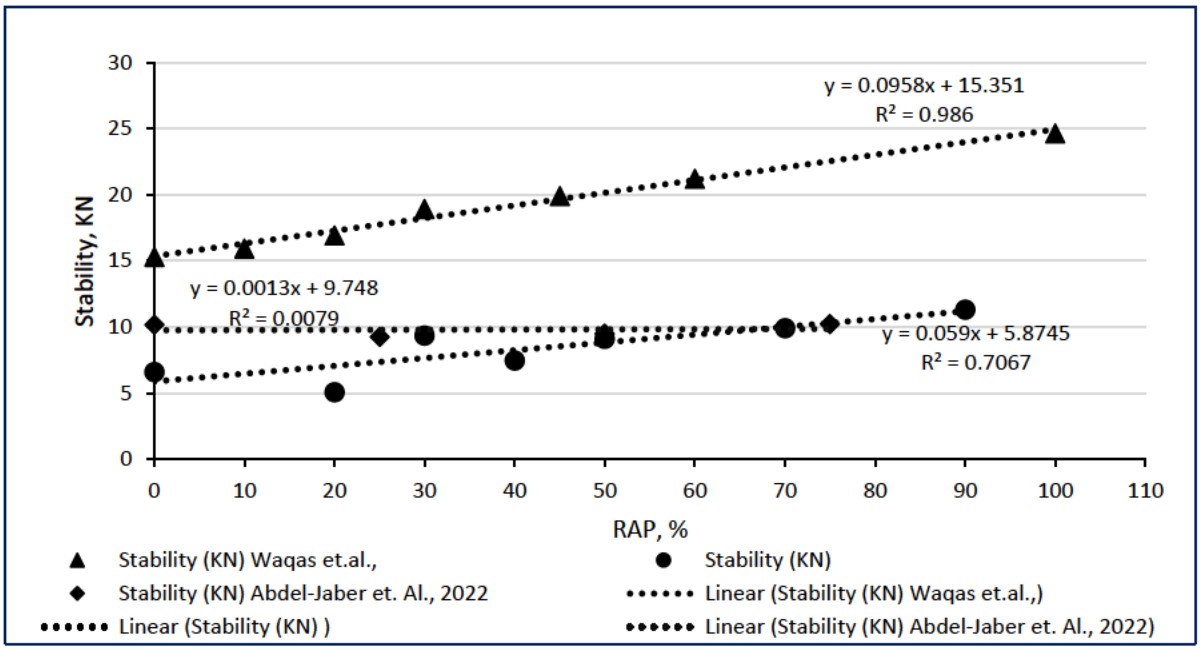


Figure 7-15 comparison of stability values

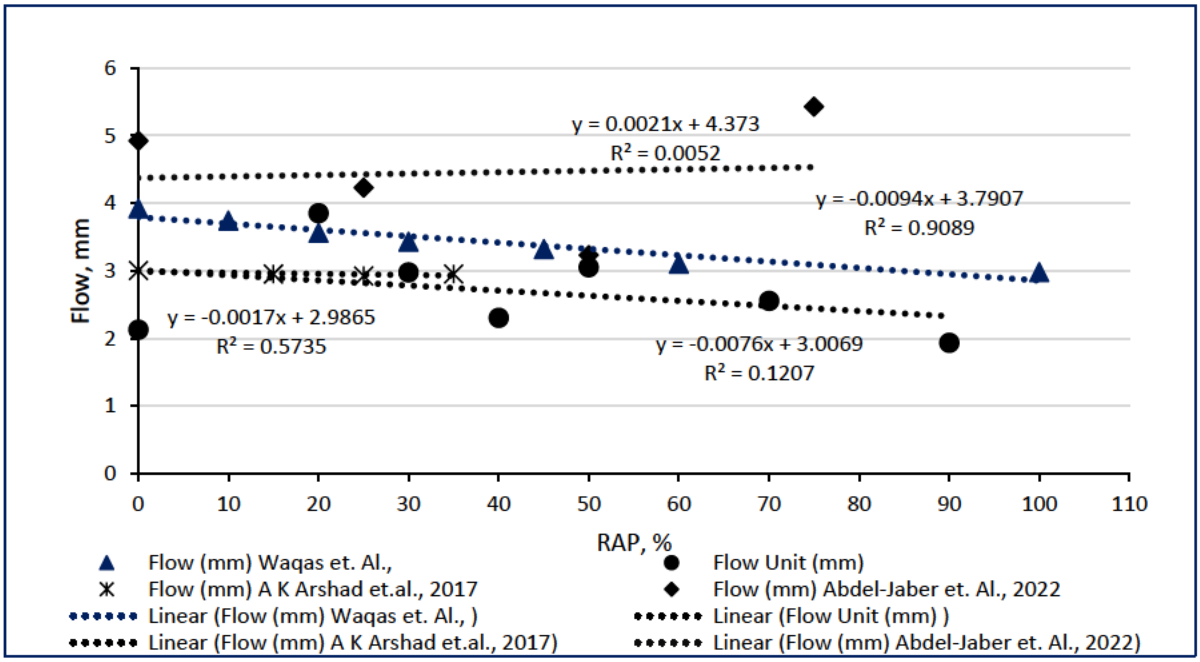


Figure 7-16 Comparison of flow values

It was observed that RAP materials properly retrieved, stockpiled, and used in a carefully mixed design will give satisfactory results and can be confidently utilised in maintenance and rehabilitation of pavements. For other uses of RAP materials, such as in the base course, is underutilising and waste of a good material, and thus it is advisable that, unless it is totally necessary, to avoid using it for such purposes.

7.3.2 Indirect tensile strength test (ITS)

The indirect tensile strength test and its results are used to evaluate the quality of a laboratory prepared mix or field-recovered cores in terms of cracking potential or rutting properties of the mix. In this research work both rutting and ITS are carried out separately on samples prepared in the laboratory. The ITS test is conducted on specimens of 101.38 mm diameter and 64.1 mm thick. The test is conducted to investigate the tensile or cracking properties of the mix (Feipeng Xiao, 2018). The tensile strength values of the samples increased as the percentage of RAP increased in the mix and the increase in strength from 0%RAP to 90% RAP is about 112%, and compared to 50% is about 82% as shown in Figure 7-17. For 20 % RAP content the increase in strength is only 2.7%, showing that the increased amount of RAP in HMA mix provides a better performance with respect to ITS. Other researchers have also indicated that as the RAP percentage increased the ITS also increased, and indicated that the increase of ITS from 0% RAP to 50% RAP is about 65% (Chaitanya, 2016). Another research study indicated that for 100%RAP content the maximum value of ITS was obtained (Hand, et al., 2022). While the ITS values increased with %RAP increment in the mix, it is also observed that inclusion of RAP in the mix improved the fatigue life of the HMA (Imad L. Al-Qadi, 2014).

Figure 7-16 show that as RAP content is increased the tensile strength values also increase. This study also confirms the findings of other researchers' (Chaitanya et al., 2016) in that inclusion of high RAP content improves the fatigue life of asphalt.

This study showed that inclusion of RAP HMA improved its resistance to cracking and rutting of the HMA. Therefore, the use of RAP materials in higher proportions in HMA mixes is encouraged. It should be noted that the maximum performance of pavements constructed with RAP containing HMA, detailed analysis of RAP materials and pure HMA mixes shall be carried out separately before mixing them together. This must be carried out on a project-by-project basis, as RAP from different locations have different characteristics.

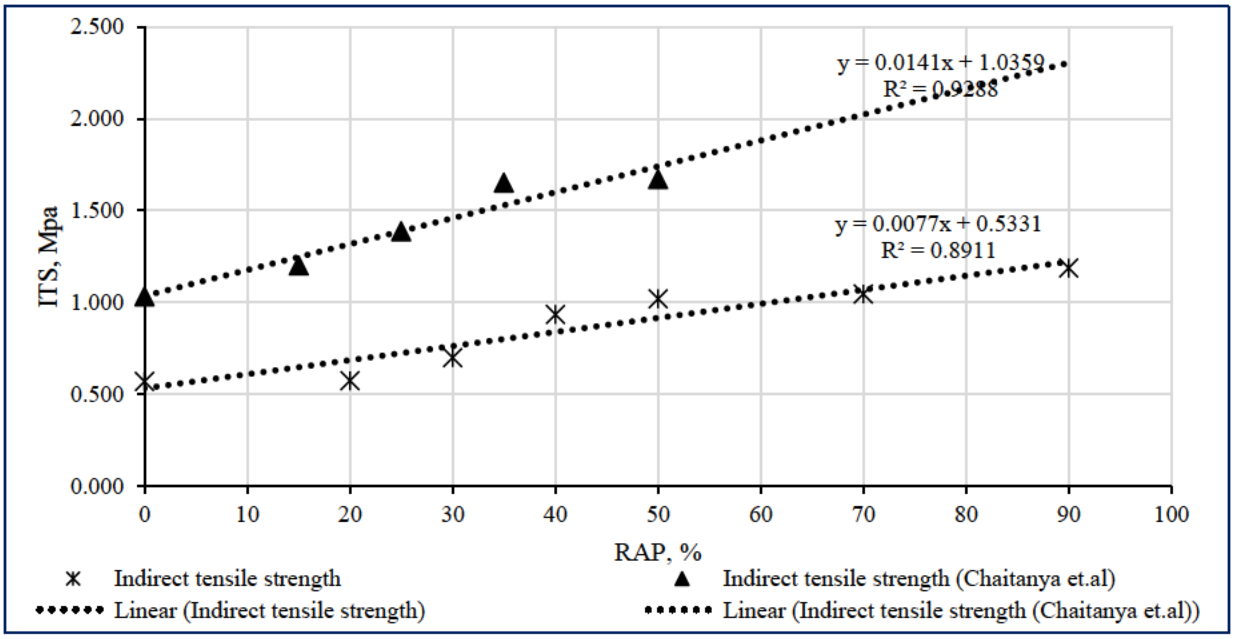


Figure 7-17 Tensile strength development with RAP content increase

7.3.3 Resilient Modulus

Bituminous Bituminous mixtures are not elastic but they show permanent deformation due to repeatedly applied loads (Galan, 2020). However, if the applied load is small enough compared to the strength of the material, the deformation after each repeated applied load is recoverable. Therefore, the rigidity obtained when the ratio between the deviator stress and the recoverable strain of bituminous mixtures remains constant after repetitive loads is called resilient modulus, M_R. (Galan, 2020). The resilient modulus was estimated to evaluate the stiffness of RAP containing mixes. It was estimated from the ITS test results using an empirical formula. The formula used is obtained from (Chaitanya, 2016) and (Galan, 2020)

Results for the M_R as shown in Figure 7-18. indicate that 20% and 30% RAP have shown lower values compared to the mix without RAP (control mix). Some research (Mivehchi, 2022) indicated that mixes with low RAP content between 0% and 20% showed poor performance with respect to cracking. This trend can be observed here also and for 20% RAP the stiffness of the mix was lower than that of no-RAP mixes. However, beyond 20% RAP content, resilient modulus increased with increase in RAP content. The influencing factor for such a performance can be attributed to aggregate gradation and angularity, binder content, air voids and percentage of RAP in the mix (Mivehchi, 2022). This should be considered as a future work as it is not the main objective of this study. The results also indicate that as the proportion of RAP increases, stiffness of the mix also increases. The maximum value of M_R is for a mix containing 90% RAP and the minimum is for 20%RAP content. The highest M_R value is more than in the control mix (without RAP case) by 132% and the lower M_R is less by 45% from the control mix. This is also confirmed by other research where mixtures with 100% RAP obtained the maximum resilient modulus under both dry and wet conditions (Hand, et al., 2022).

It is also noted that the binder from the RAP will have higher stiffness due to age hardening and this will have an influence on the stiffness of mixes containing RAP materials (Chaitanya, 2016). Rejuvenators improve performance of totally recycled hot mixes (Hugo Silva, 2012) and therefore, it is worth considering the use of rejuvenating additives to avoid problems associated with higher stiffness when high or totally recycled hot mixes are used.

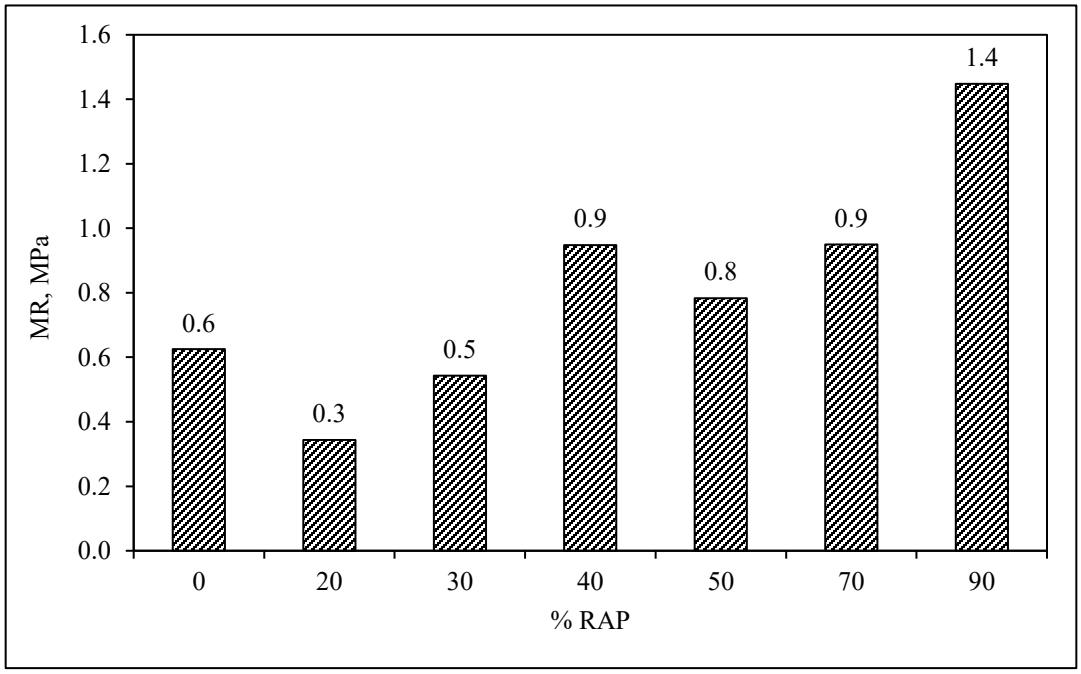


Figure 7-18 Calculated Resilient Modulus values

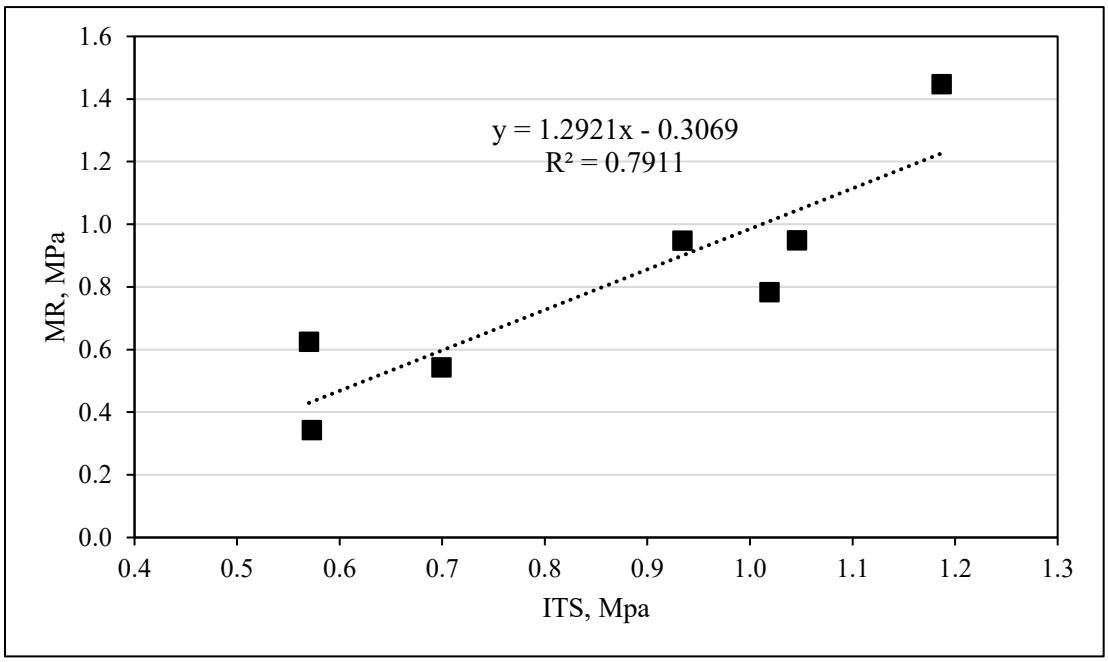


Figure 7-19 Correlation between MR and ITS

Although, it was desirable to conduct the test for resilient modulus, the apparatus was not available at the RRC and it could not be carried out. Therefore, it was decided to obtain the values indirectly from the ITS test. Based on the calculated M_R and the ITS results, if there is a correlation between the two values was investigated. Accordingly, as can be seen from Figure 7-19 it was found that there is a good correlation and thus, the values of M_R can be used to indicate the stiffness of the mix.

7.3.4 Rutting

Rutting is a longitudinal deformation or depression of a pavement along the wheel path caused by wheel loads through an action of repeated loading. The rutting potential of HMA containing RAP materials was measured using wheel rutting equipment on specimens prepared and compacted using the slab compactor. Samples were prepared with sizes of 305 mm x 305 mm x 50 mm. The compacted specimens and the mould were cooled at normal room temperature for 24 hrs and then the samples and the mould were heated in an oven for 16 hrs at a temperature of 60 ºC. The samples were prepared by compacting them using a linear kneading compactor with a compaction load of 800 N. Rutting was measured at 20,000 cycles with an applied load of 705± 4.5 N at 60 ºC using the wheel tracking tester machine.

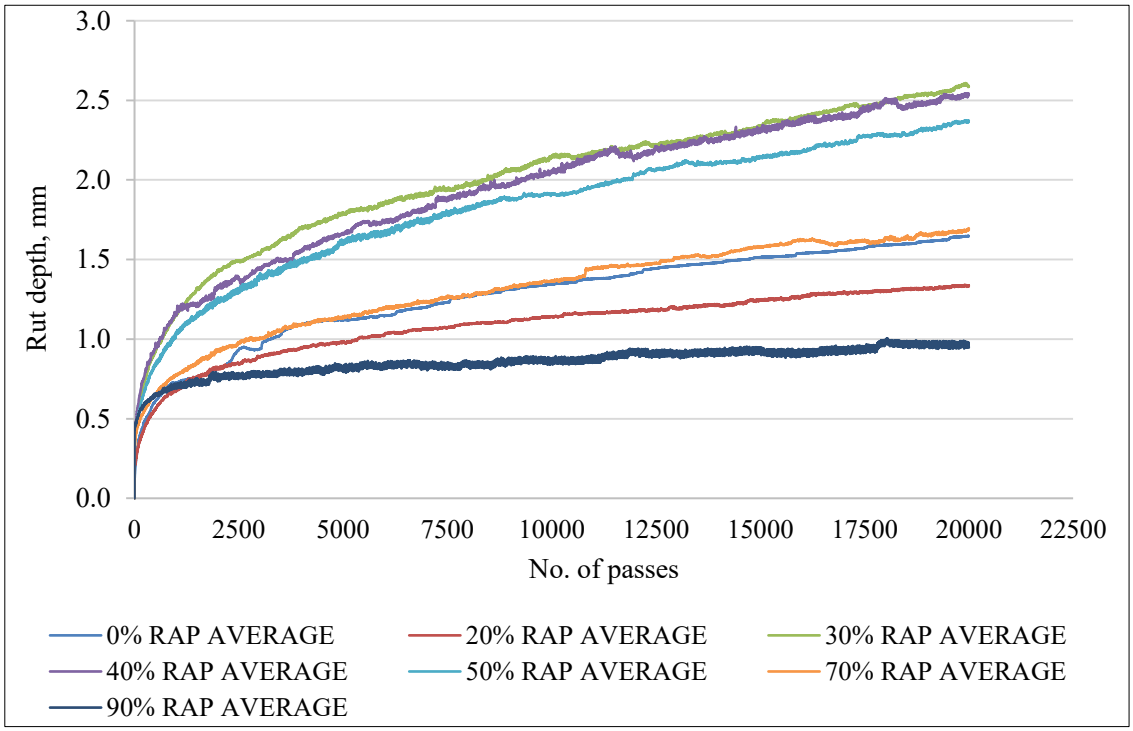


Figure 7-20 Measured Rut depths at 20,000 passes

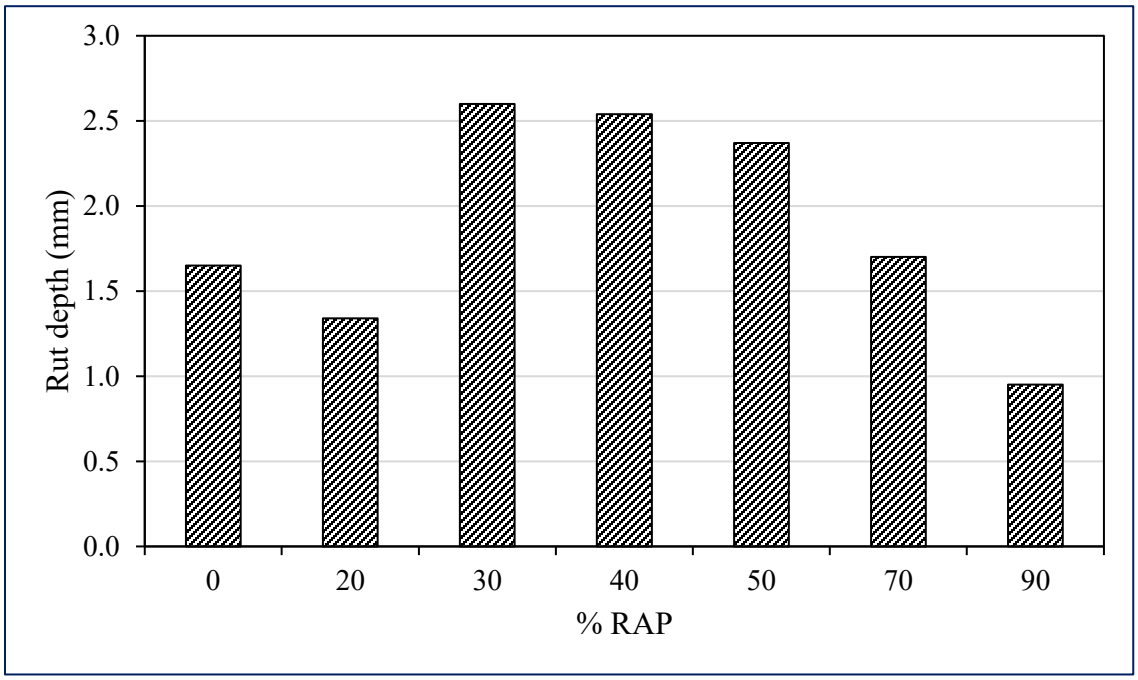


Figure 7-21 Average values for rut depths

Figure 7-20 and 7-21 shows the change in rut depth relative to the control mix. For the control mix (HMA without RAP) the rut depth was 1.7 mm and this is the value used to compare rut depths of mixes containing RAP materials. The HMA with 90% RAP exhibited the lowest rut depth of 1.0 mm while 30% and 40% RAP content had the highest rut depths of 2.6 mm and 2.5 mm respectively. Compared to the HMA without RAP, 90%RAP content showed a decrease from the control mix by 42%. The rut depth for HMA containing 30% RAP increased from the control mix by 58% and the HMA containing 40% increased by 54%.

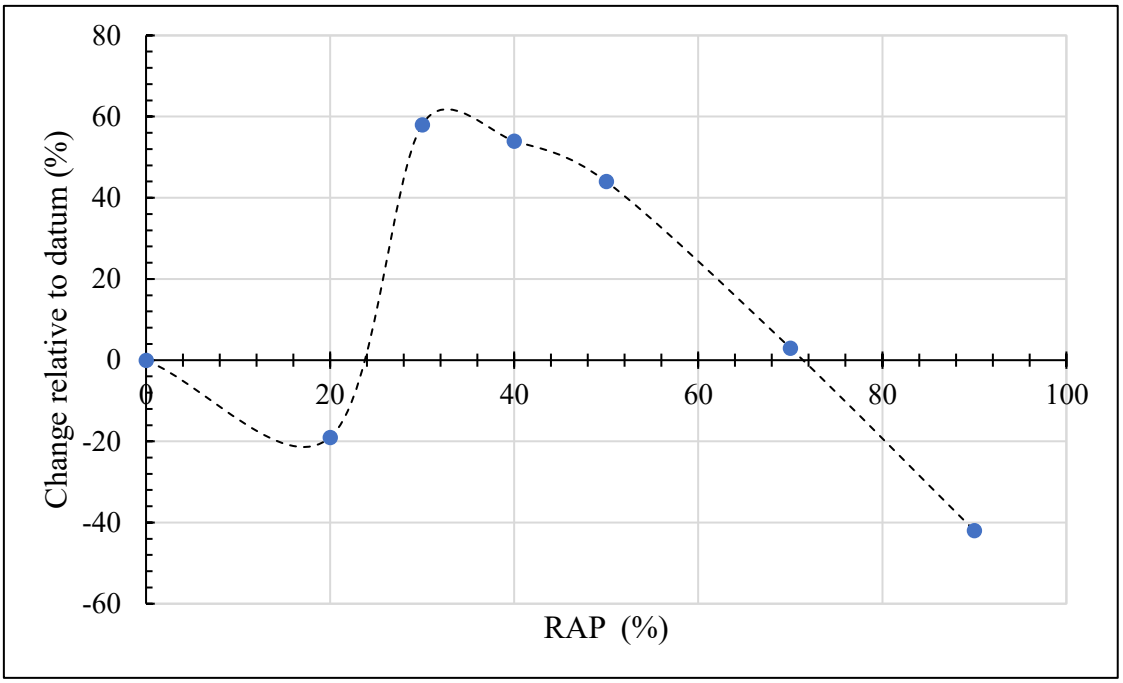


Figure 7-22 Change relative to datum for rut depths

In the rut depth measurement of HMA containing different proportions of RAP it is observed that as the RAP increased in the mix the rut resistance of the mix showed an improvement, especially with the higher proportion mixes, compared to the control mix. However, it should also be noted that mixes with 30%, 40%, and 50% RAP indicated rut depths higher than the control mix, while 20% RAP content had a lower rut depth. In general, increasing the RAP content improved the rut resistance of the mix and resulted in decreasing rut depths. However, it should also be noted that cracks can be problems as evidenced by the ITS result, where a higher RAP content resulted in lower resistance to cracking.

The resilient modulus results show that the stiffness of the mix increased for RAP content over 40%. The rut resistance of the mix was expected to increase according to extensive tests conducted on high percentages of RAP by (Rafiq, 2020), however, it was only for 20% and 90%RAP content that the rut depth was better than the control mix.

Therefore, from the test results it can be concluded that an increased amount of RAP up to 90% indicated improvements in the performance of the mix in terms of rutting. Further study is

required to investigate why RAP percentages of 30%, 40%, and 50% have shown significantly higher values of rut depths compared to the control mix.

7.3.5 Summary of discussion on laboratory test

The test results on mixes containing RAP have generally shown improvement as the RAP percentage increased. The main durability measures of RAP materials are rutting resistance and cracking on the surface of the pavement (Isacsson, 2006), and in this research these two parameters were tested and the results indicated better performances. The literature indicates that recycled asphalt compared to new asphalt shows no significant difference in its performance as long as the material components, composition and the construction method are not different (Isacsson, 2006) (Kandhal, 1997). This indicates that using RAP material will provide an equal or better performance and this research has confirmed the same. In addition, adding more RAP material in the mix will increase the performance.

In terms of the Marshall test results, stability and flow values for mixes containing RAP satisfied the requirements of the ERA specification. It was found that a RAP percentage content over 50% showed better stability with regard to heavily trafficked roads carrying over 5 million ESA. The flow values were within the specification limit for mixes containing RAP of between 20% and 90%. Generally, the flow and stability values showed an increasing trend with the increase of the RAP percentage in the mix. The ITS values have significantly increased at higher RAP contents. The rate of increase of the ITS value increased as the RAP percentage increased and for 90% RAP content the value was 112% of the control mix (without RAP); while for 20% RAP content it was only 2.6%. This indicates using a higher RAP content improves the ITS.

With increased RAP content in the HMA mix the performance improved indicating that recycling of old asphalt pavement material is a beneficial exercise. It is also to be noted that RAP material if properly prepared and used in asphalt mix, has a high potential of improving the resistance to rutting and cracking.

Therefore, from the laboratory tests and analysis of the results, mixes containing RAP materials can be used for pavement construction and rehabilitation as follows.

1. All RAP content, 20%, 30%, 40%, 50%, 70% and 90% can be used on low traffic roads carrying 1 million ESA, provided that it is economically justified for the lower RAP

percentages, because using lower RAP content means using a higher content of virgin materials.

2. All RAP content tested in this research can be used on medium traffic roads carrying 1-5 million ESA.
3. Mixes containing RAP contents greater that 30% can be used on high traffic roads carrying more than 5 million ESA.

7.4 Summary of major achievements of the study

The major achievements in this study are presented by evaluating with the main objectives and research questions as follows.

i. The first objective was to create an understanding of asphalt pavement recycling in terms of its application, advantages and limitations. This objective was met through a detailed systematic review of the literature in Chapter Three, where identification of recycling types, their application and advantages and limitations were summarised and presented in Table 3.3. Further applications were considered in different climates: semi-arid, sub-humid and tropical-humid. This was supported by laboratory investigations of recycled pavement.

ii. Undertaking a systematic review was conducted as one of the main objectives and was met through Chapter Three where detailed study on selected and relevant literature greatly helped in obtaining good knowledge and detailed information regarding asphalt pavement recycling. Asphalt pavement recycling literature is much concentrated in the developed countries. It is noted that a documented recycling exercise could not be obtained for developing or listing income countries where sufficient information to establish evidence on the experience, advantages and limitations of recycling in developing countries.

    A systematic review of the literature, however, delivered all necessary information on the experience of implementation, performance and benefits of asphalt pavement recycling that can also be translated to the developing countries. The result of the systematic literature review has shown the gap in recycling of asphalt pavements in developing

countries, and thus, there is a need for further research work to be conducted, including trial section construction and monitoring, which will provide necessary information to encourage its implementation.

iii. Developing a selection method for identifying the best performing asphalt pavement recycling method objective was met through Chapter Three and Chapter Four. Mainly in Chapter Four, an asphalt pavement recycling selection method was developed by utilising the information gathered in the systematic literature review and questionnaires developed for this purpose. Detailed work is presented in Chapter Four. Accordingly, cold in-place, cold in-plant and full depth reclamation had the highest preferences as a result of the selection method.

iv. Chapter Five presented the development of a policy framework for asphalt pavement recycling. Through the systematic literature review and questionnaires, it was found that there was a lack of an appropriate guide for the implementation of asphalt pavement recycling in Ethiopia. The questionnaires focused only on selected professionals at management level who are believed to understand asphalt pavement recycling and its associated implementation challenges because of a lack of proper guidance. Based on that policy, statements that help to support and guide asphalt pavement recycling were established. The policy statements advocate the benefits of recycling, recognise and instruct the provision of proper resources and necessary support from the government.

v. Performance of pavements constructed using RAP containing mixes was evaluated in the life cycle cost analysis carried out in this study. Accordingly, RAP containing mixes performed well in the tropical humid climate where the highest net present value (NPV) is obtained. In the semi-arid climate, economically, RAP performed relatively poorly compared to the sub-humid and tropical-humid climates. The life cycle cost analysis showed that it is more advantageous to recycle asphalt pavements in a tropical-humid climate.

vi. A recycled asphalt pavements' laboratory investigation was carried out in Ethiopia to assess the performance of different proportions of RAP materials incorporated in asphalt mixes. The result indicated good performances especially at higher percentages of RAP

content. Both the laboratory investigation and the LCC analysis have provided important findings:

- A higher RAP content has better economic benefit in terms of life cycle cost, indicating recycling asphalt pavement would have significant cost savings when used in the rehabilitation of asphalt pavements.
- Use of RAP materials in mixes improved the performance of pavements in terms of crack and rutting resistance.
- It was also found that more tests must be carried out on samples from different sources and additional parameters of performance measurement, such as construction and monitoring of trial sections, will provide more information which is needed to develop standards and design guides for local conditions.
- Recycling of asphalt pavement in tropical regions, where Ethiopia is also located, has proved to yield good performance both technically and economically.

Therefore, from this study we can conclude that recycling asphalt pavement in a hot climate performs well and this is presented in detail in Chapter Six.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

Asphalt pavement recycling is currently widely and mostly used in developed countries due to its economic benefit and reduced environmental impact. However, greater use of RAP would also benefit developing countries for the same reasons, but for various reasons it has not been taken up as normal practice. This research is aimed at investigating how it can be used in developing sub-Saharan countries such as Ethiopia. The need to recycle existing asphalt pavement is increasing and it should be better investigated with regard to its implementation, including selection methods and policy framework. Sufficient information on performance of RAP materials is not available in developing countries and thus laboratory experiment was needed to provide data for life cycle cost analysis.

8.2 Conclusions

Conclusions drawn from this study are listed below with respect to each research objective.

A. Objective 1- Systematic literature review of RAP

i. Asphalt pavement recycling is cost effective, energy saving, economically and environmentally sustainable approach to pavement rehabilitation.

ii. Bulk of the literature on laboratory investigations and case studies about RAP originated in the developing countries. Many of these countries have developed well established frameworks and national standards for their application.

iii. Many of the literatures discussed on cold in-place and cold in-plant suggesting that they are possibly the most favoured techniques of recycling.

iv. Asphalt pavements may be recycled repeatedly making it the most recycled material.

v. Performance of pavement made from RAP containing mixes perform equally or better compared to virgin mixes as long the design and construction processes are followed correctly.

vi. Hot mix manufactured by using RAP materials improves durability of pavements and showed good resistance to stripping.

vii. Road construction and maintenance involve production of large quantities of material that significantly contribute to greenhouse gas emission. Recycling, therefore, significantly reduces these emissions through reusing materials and cutting amount of production of materials.

B. Objective 2 – RAP technologies for Ethiopia

i. Following an extensive review and consultation with experts, it was suggested that the most appropriate recycling methods for developing countries, such as Ethiopia, were Cold In-Plant, Cold In-Place recycling and Full Depth Reclamation. This was primarily due to need for techniques which required more sophisticated equipment greater expertise.

ii. In order to encourage the use of RAP in Ethiopia it may be necessary to put in place a policy framework and incentives for both public and private contractors.

iii. There is shortage of local expertise in the use of RAP in Ethiopia. It was thus necessary to build local expertise in both consulting engineering and contracting organizations to encourage the use of RAP.

C. Objective 3 – Laboratory investigation of RAP

i. A laboratory study of RAP recovered from roads in Ethiopia showed that the performance of HMA containing RAP was better than mixes without RAP in terms of rut and crack resistance.

ii. All RAP contents 20%, 30%, 40%, 50%, 70% and 90% can be used on low traffic roads carrying up to 1million ESA, provided that it is economically justified for lower RAP percentage. This is because lower RAP content asphalt required higher content of virgin materials.

iii. All RAP content tested in this research can be used on medium traffic roads carrying 1-5 million ESA

iv. Mixes containing RAP contents greater that 30% can be used on High traffic roads carrying more than 5 million ESA.

v. As RAP content increased from 20 to 90% performance of the mix in terms of rutting and crack resistance have also showed increasing trend. Higher rutting resistance is observed for RAP content of 70% and 90%.

D. Life cycle cost analysis (LCCA)

i. LCCA conducted using HDM4 indicated that saving obtained for 90% RAP was higher than the base case (asphalt without RAP) by 1.7% for Sub-Tropical climate. For Sub-humid and Sem-arid climates savings obtained by using 90% RAP is 1.49% and 1.14% higher compared to base case.

ii. Savings on life cycle cost increased as the RAP percent increased for all three climates, semi-arid, sub-humid and tropical-humid.

iii. Agency cost saving increased as RAP percent increased, and the highest saving is obtained in the tropical-humid climate.

iv. LCCA result indicated that using RAP materials will give 22% to 27% saving on Agency cost.

v. To achieve an agency cost saving of 22% the RAP content should be 50% or more. However, the RAP contents used in this study have all showed savings on agency cost of 7% on 20%RAP and 49% on 90%RAP contents.

vi. Vehicle operating cost and Road user costs are unaffected compared to base case (0 RAP) as a result of using RAP.

This research has indicated how the Asphalt Pavement Recycling can be implemented in developing countries. It showed the procedures and methods to be followed in devising selection criteria and their evaluation to select best suited recycling type. Policy framework developed in

this research will enhance the decision-making process in implementing recycling of asphalt pavements in developing countries. Specially to facilitate allocating appropriate level of budget and availability of the scarce foreign currency.

8.3 Recommendations

Although this study has met its objective, there are limitations that need to be further investigated. It is believed that this research is the first step in developing the use of RAP. As such further studies are required for its widespread use in developing countries. in. Area recommended for further studies are shown below.

1. Asphalt pavement recycling methods and their application are not well developed for developing countries and thus very limited information is available. There is thus a need to develop technologies that are affordable and of lesser sophistication for use in developing countries.

2. Performance of RAP materials can be further investigated through construction of trial sections and monitoring performance parameters such as rutting, cracking and moisture susceptibility.

3. More studies need to conducted to fully understand the characteristics of existing aged asphalt with recycling as RAP in mind in the context of existing climatic conditions.

4. In this research, testing was limited to Marshal test, heel tracking Test and ITS due to shortage of laboratory equipment. Nonetheless the data collected enabled to assessment the value of using RAP. It is suggested that more extensive testing of existing RAP materials is undertaken to ascertain performance. Both RAP material and bitumen from diverse range of climatic conditions may be included in the study.

Once the engineering properties are known with high degree of confidence, economic analysis and test sections may be constructed to prove the RAP construction technology and performance.

9 REFERENCES

A K Arshad, 2017. *Marshall properties and rutting resistance of hot mix asphalt with variable reclaimed asphalt pavement content.* Boston, IOP Publishing.

Abdalrhman et al., 2020. A review of the use of reclaimed asphalt pavement for road paving application. *Jornal Teknologi.*

Abdel-Jaber, M. et al., 2022. Mechanical Properties evaluation of asphalt mixtures with variable contenets of reclaimed asphalt pavement (RAP). *Results in Engineering,* Volume 14.

Ahmed et al., 2020. Recycleed aggregate concrete from large scale production to sustainable field application. *Construction and building materials,* pp. 1-13.

Alemayehu & Andrew, 2015. *Perfromance Review of Foamed Bitumen in Ethiopia.* Sun City, s.n.

Alexander J. et al., 2020. Variability of reclaimed asphalt pavement (RAP) properties within a State and its effect on RAP specifications. *Transportation Research Record, TRR,* 2674(6), pp. 73-84.

Al-Qadi et al., 2014. Reclaimed Asphalt Pavement - A Literature Review.

Amarh et al., 2022. Evaluating the potential Environmental Benefits of Cold Recycling-Based Methods for flexible pavements rehabilitation in Vergina. *Transport Research Record (TRR),* Volume 2676(6), pp. 75-86.

Andreen, Rocheville & Ksaibati, 2011. A Methodology for Cost/Benefit Analysis of Recycled Asphalt Pavement (RAP) in Various Highway Applications. *Transportation Research Board.*

Andreen, Rocheville & Ksaibati, 2012. A Methodology for Cost/Benefit Analysis of Recycled Asphalt Pavement (RAP) in Various Highway Applications. *Transportation Research Board .*

Angela Farina, M. C. Z. E. S. G. A. B., 2017. Life Cycle assessment applied to bituminous mixtures containing recycled materials: Crumb rubberand reclaimed asphalt pavement. *Resources, Conservation and Recycling,* pp. 201-212.

APA, 2016. Asphalt - The sustainable pavement.

ARRA, 2001. *Basic Asphalt Pavement Recycling Manual.* s.l.:s.n.

Asphalt Recycling and Reclaming Association , 1992. *An overview of recycling and reclamation methods for asphalt pavement rehabilitation,* Maryland: ARRA.

Assaf, H. & Abdo, A., 2021. Life cycle assessment of ncorporating recycled materials in pavement design. *Journal of king Saud University.*

Ayeditan et al., 2020. Evaluation of mixture perfromance recycle asphalt pavement materials as base layer with or without rejuvinator into the asphalt. *Journal of Wuhan University of Technology,* pp. 579-594.

Barros, L. et al., 2019. Implication of including Reclaimed Asphalt Pavement Materials to Perfromance of Balanced Aspahlt Concrete Mixes. *Transport Research Record (TRR),* Volume 2673(12), pp. 670-678.

Berhanu, A., 2022. *The Evaluation Using Life Cycle Approach of Different Types of Road Pavement Surfacing Subjected to Climate Impact,* Birmingham: University of Birmingham.

Bocci et al., 2014. Full-depth reclamation for the rehabilitation of local roads: a case study. *International Journal of Pavement Engneering,* pp. 191-201.

Bongsuk Park et al., 2020. Approach for determination of Maximum reclaimed asphalt pavement content in polymer-modified aspahlt mixture. *Transport Research Record (TRR),* Volume 2674(6), pp. 420-430.

Bozyurt, O., Edil, T. B., Tinjum, J. M. & Bensson, C. h., 2012. *Resilient modulus of recycled asphalt pavement and recycled concrete aggregate.* s.l., s.n.

Buchler, S. et al., 2018. Wearing course mixtures prepared with high Reclaimed asphalt pavement content modified by rejuvinators. *Transportation Research Record, TRR,* 2672(28), pp. 96-106.

Burrow, P. R. S. M. G. G. E. H., 2016. What is the evidence supporting the technology selection for low-volume, rural roads in low-income countries and what evidence is there to support the sustainability of different rural road technology? A systematic review.. *ICE,* 169(TR6), pp. 366-377.

Byrne & David, A., 2005. *Recycling of asphalt pavements in new bituminous mixes.* s.l.:s.n.

Cantrell, L., Wen, H. & Wang, L., 2022. Development of a model to estimate percentage of Recliamed Asphalt Pavement (RAP) Binder contribution based on design and perfromance of Super High RAP Mixes. *Transportation Research Record (TRR).*

Carswell & Nunn, 2004. *A guide to the use and specification of cold recycled materials for the maintenance of road pavements.,* s.l.: TRL.

Carvalho et al., 2010. *Perfromance of Recycled Hot Mix Asphalt Overlays in Rehbailitation of Flexible Pavements.* s.l., s.n.

Chaitanya et al., 2016. *Fatigue perfromance of bituminous mixes containing RAP material.* s.l., s.n.

Chaoyang & Jiang, 2020. *Recent development in high-content reclaimed asphalt use.* s.l., s.n.

Chen et al., 2007. *Evaluation of Long Term Field performance of Cold In-Place Recycled Roads: Field and Laboratory Testing.,* s.l.: s.n.

Cochran, K., 2006. *Construction and demolition debries recycling: Methods, markets, and policy,* s.l.: University of Florida.

Collings, Lewis, A. & DC, 1999. *Cold in-place recycling: A relevant process for road rehabilitation and upgrading.* Kloof, CAPSA 99.

Copland, 2011. Reclaimed aspahlt pavement in asphalt mixtures: State of the practice.

DAvid Tranfield, D. D. a. P. S., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Teview. Volume 14, pp. 207 - 222.

Diefendefer et al., 2012. In-Place Pavement Recycling on I-81 in Virginia. *Journal of the Transportation Research Board,* pp. 21-27.

Diefenderfer et al., 2015. Initial perfromance of Verjinia's Interstate 81 In-place pavement recycling project. *Transport Research Record (TRR),* pp. 152-159.

Diefenderfer et al., 2020. Development and assessment of test for construction of aspahlt treated Cold Recycled Pavements. *Transportation Researh Record (TRR),* Volume 2674(3), pp. 189-198.

Diefenderfer et al., 2022. Structural perfromance of an asphalt pavement containing cold central plant recycling and full depth reclamation. *Transportation Research Record, TRR,* pp. 1-11.

Diefenerfer et al., 2016. *Structural Study of Cold Central Plant Recycling at the National Centre for Asphalt Technology (NCAT) Test Track,* s.l.: s.n.

E. Alkins et al., 2008. Sustainable PAvements: Environmental, Economic, and Social Benefits of In Situ Pavement Recycling. pp. 100-103.

EAPA, 2014. *Asphalt the 100% recyclable construction product.* Brussels: EAPA.

EAPA, 2017. *Asphalt in figures, 2015,* Brussels: EAPA.

Earland, M. a., 1999. *Design gude and specification for structural maintenance of highway pavements by cold in situ recycling,* s.l.: TRL.

Edil, L., Tinjum & Benson, 2010. Quantitative assessment of environmental and economic benefits of recycled materials in highway construction.. *TRB,* pp. 138-142.

Edward J. Hope, D. s. L. G. M. F. S. S., 2015. *Feasibility of Reclaimed Asphalt Pavement (RAP) Use as Road Base and Subbase Material,* Richmond: Virginia Center for Transportation Innovation and Research.

El-Hamrawey et al., 2015. Durability of hot asphalt mixtures containing reclaimed asphalt pavements. *Open access library journal.*

Endale, A. A., Ghataora, G. S. & Burrow, M. P. N., 2022. Asphalt pavement cold recycling and basic characteristics of RAP materials and their application. *Journal of Civil Engineering and Architecture,* pp. 38-51.

Essenwa et al., 2013. 100% Recycled Asphalt Paving, Our Experience.

Ethiopian Roads Authority, 2013. *Pavement Design Mannual, Volume 1, Flexible Pavements.* Addis Ababa: Ethiopian Roads Authority.

Fan Gu et al., 2019. Structural perfromance and sustainability assessment of cold central-plant and in-place recycled asphalt pavements: A case study. *Journal of cleaner production,* pp. 1513-1523.

Farina et al., 2017. Life Cycle assessment applied to bituminous mixtures containing recycled materials: Crumb rubberand reclaimed asphalt pavement. *Resources, Conservation and Recycling,* pp. 201-212.

Feipeng Xiao et al., 2018. A literature Review on cold recycling technology of asphalt pavement. *Construction and building materials,* pp. 579-674.

Franke & Ksaibati, 2015. A Methodology for Cost/Benefit Analysis of Recycled Asphalt Pavement (RAP) in Various Highway Applications.. *International Journal of Pavement Engneering, 2015,* pp. 660-666.

Fujie Zhou et al., 2007. Case Study: Evaluation of Laboratory Test Methods to characterize Permanent Deformation Properties of Asphalt Mixes. *International Journal of Pavement Engineering,* Volume 4(3), pp. 155-164.

Fujie Zhou et al., 2013. *Literature Review: Perfromance of RAP/RAS Mixes and New Direction,* Austin: s.n.

Galan et al., 2020. Evaluation of the Resilient Modulus of Hot Mix Asphalt Made with Recycled Concrete Aggregates from Construction and Demolition Waste. *Sustainability.*

Gerardu & Hendriks, 1985. *Recycling of road pavement materials in the Netherlands,* s.l.: s.n.

Giani, M. I., Dotelli, G., Brandini, N. & Zampori, L., 2015. Comparative life cycle assessment of asphalt pavement using reclaimed asphalt, warm mix technology and cold in place recycling. *Resources, Conservation and Recycling,* pp. 224-238.

Gubbala Chaitanya, M. R. S. K. S. R., 2016. *Fatigue perfromance of bituminous mixes containing RAP material.* s.l., s.n.

Habbouche et al., 2022. Review from multiple perspectives for the state of the practice on the use of recycled asphalt materials and recycling agents in asphalt concrete surface mixtures. *Transportation Research Record, TRR,* 2676(4), pp. 407-420.

Hand, A. et al., 2022. *Evaluation of Low Volume Roads Surfaced with 100% RAP Millings.* [Online] Available at: https://doi.org/10.3390/ma15217462 [Accessed 06 April 2023].

Hanson, K. R. & Copland, A., 2015. *Asphalt Pavement Industry Survey on Recycled Materials and Warm-mix Asphalt usage,* Lanham: National Asphalt Pavement Association.

Hasan, U., Whyte, A. & Jassmi, H. A., 2020. Life Cycle Assessment of road works in United Arab Emirates: Recycled Construction Waste, reclaimed asphalt pavement, warm-mix aspahlt and nblast furnace slag againest traditional approach. *Journal of Cleaner Production,* p. 16.

Hendriks, G. a., 1985. *Recycling of road pavement materials in the Netherlands,* s.l.: s.n.

Holt et al., 2009. *Full Depth Remediation of Roads Using Portland Cement.* Vancouver, s.n.

Hope et al., 2015. *Feasibility of Reclaimed Asphalt Pavement (RAP) Use as Road Base and Subbase Material,* Richmond: Virginia Center for Transportation Innovation and Research.

Horvath, 2004. *A life-cycle analysis model and decision-support tool for selecting recycled versus virgin materials for highway applications. University of California at Berkeley.,* s.l.: s.n.

Horvath, A., 2003. *Life-cycle environmental and economic assessment of using recycled materials for asphalt pavements. University of California Transportation Center.,* s.l.: s.n.

Hugo Silva, J. O. a. C. J., 2012. Are totally rcycled hot mix asphalts sustainable alternative for road paving. *Resource conservation and recycling* .

Imad L. Al-Qadi, M. E. S. H. C., 2007. *Reclaimed Asphalt Pavement- A literature review,* Urbana: University of Illinois, Cuvil Engineering Studies .

Imad L. Al-Qadi, M. E. S. H. C., 2014. Reclaimed Asphalt Pavement - A Literature Review.

International Labour Organization , 2013. *Bituminous Sealing of Low Volume Raods using Labour Based Methods, Ethiopian Roads Authority.* Addis Ababa: International Labour Organization.

International Labour Organization, 2013. *Construction of Low Volume Sealed Roads, Good Practice Guide to Labour Based Methods,* Pretoria: International Labour Organization.

Isacsson, R. K. a. U., 2006. Material-Related Aspects of Asphalt Recycling - State-of-the-Art. *Journal of Mterials in Civil Engineering,* 18(1), pp. 81-92.

J. A. Epps et al., 1980. *Guidelines for recycling pavement materials,* Washington: Transportation Research Board, National Research Council.

J. Mallela et al., 2006. *Peformance Evaluation of Cold In-Place Recycling Projects in Arizona,* s.l.: s.n.

Jahanbakhsh et al., 2020. Sustainable asphalt concrete containing high reclaimed asphalt pavements and recycling agents: Perfromance assessment, cost analysis, and environmental impact. *Journal of cleaner production,* pp. 1-20.

Jahangiri et al., 2019. Perfromance Evaluation of Asphalt Mixtures with Reclaimed Asphalt Pavement and Recycled Aspahlt Shingles in Missouri. *Transportation Research Record (TRR),* Volume 2673(2), pp. 392-403.

Jitareekul, P., 2009. *An Investigation into Cold In-Place Recycling of Asphalt PAvements.* s.l.:s.n.

Jones, S. L. a. D., 2015. *Pavment Recycling: Literature Review on Shrinkage Crack Mitigation in Cement-Stabilized Pavement Layers,* s.l.: s.n.

Juan J. Galan, L. M. S. A. R. P. I. P., 2020. Evaluation of the Resilient Modulus of Hot Mix Asphalt Made with Recycled Concrete Aggregates from Construction and Demolition Waste. *Sustainability* .

Kadrmas et al., 2002. *Performance-Related Tests and Specifications for Cold In-Place Recycling: Lab and Field Experience.* s.l., s.n.

Kandhal, P. S. & Mallick, R. B., 1997. *Pavement Recycling Guidelines for State and Local Governments - Participant's Reference Book,* s.l.: s.n.

Kang-Won Wayne Lee, M. M. a. A. S., 2014. Cold In-Place Recycling as a sustainable Pavement Practice. *Journal of Civil Engineering and Architecture,* 8(6), pp. 680-692.

Karlsson, R. & Isacsson, U., 2006. Material-Related Aspects of Asphalt Recycling - State-of-the-Art. *Journal of Mterials in Civil Engineering,* 18(1), pp. 81-92.

Kaseer et al., 2019. A method to quantify Reclaimed Aspahlt Pavement Binder Avialability (Effective RAP Binder) In Recycled Asphalt Mixes. *Transport Research Record (TRR),* Volume 2673(1), pp. 205-216.

Khan, K. M. et al., 2012. Perfromance comparison of cold in-lace recycled and conventional HMA mixes. *Journal of Mechanical and Civil Engineering,* 4(1), pp. 27-31.

Kilpatrick et al., 2009. *Field Evaluation of a Cold In-Place Recycled Base Overlaid with Hot Mix Asphalt,* s.l.: s.n.

Kim et al., 2005. Resilient modulus of base course containing recycled asphalt pavement. *Journal of Transportation Board,* pp. 27-35.

Kim, 2014. *Designing and Constructing Strong and Durable Recycled Pavement with High Percentage of Reclaimed Asphalt Pavement (RAP),,* s.l.: s.n.

Konstantinos Mantalovas, G. D. M., 2019. THe suatainability Reclaomed Asphalt as a Resource for Raod Pavement Managament through a Circular Economic Model. *Sustainability.*

Ksaibati, Franke, R. & Khaled, 2014. A methodology for cost benefit analysis of recycled asphalt pavement in various highway applications. *International journal of pavement engineering,* 16(7), pp. 660-666.

Lee et al., 2014. Cold In-Place Recycling as a sustainable Pavement Practice. *Journal of Civil Engineering and Architecture,* 8(6), pp. 680-692.

Lee, Edil, Tinjum & Benson, 2010. Quantitative assessment of environmental and economic benefits of recycled materials in highway construction.. *TRB,* pp. 138-142.

Levis, Barlaz, Tayebali & Ranjithan, 2011. Quantifying the Greenhouse Gas Emission Reductions Associated with Recycling Hot Mix Asphalt.. *Raod Materials and Road Design, Volume 12 - No 1/2011,* pp. 57-77.

Locander, R., 2009. *Analysis of Using Reclaimed Asphalt Pavement (RAP) as a Base Course Material,* Denver: s.n.

Magar, S., Xiao, F., Singh, D. & Showkat, B., 2022. Applications of reclaimed asphalt pavement in India- A Review. *Journal of Cleaner Production.*

Mallick, Z. a. R. B., 2015. Review of very high content Reclaimed Asphalt use in plant produced pavements: State of the art. *International Journal of Pavement Engineering,* 16(1), pp. 39-55.

Mantalovas, Konstantinos & Mino, G. D., 2019. THe suatainability of Reclaimed Asphalt as a Resource for Raod Pavement Managament through a Circular Economic Model. *Sustainability.*

Martins Zaumanis, R. B. M., 2016. 100% Hot Mix Asphalt Recycling: Challenges and Benefits. *Elsevier,* pp. 3493-3502.

Ma, Y. et al., 2022. Comparative study of pavement rehabilitation using Hot in-place Recycling and Hot Mix Asphalt: Performance evaluation, Pavement life prodiction, and Life Cycle Cost Analysis. *Transport Research Record (TRR).*

Maziar Mivehchi, H. W. Y. W. a. L. W., 2022. Study of measures to design asphalt mixes including high percentages of recycled asphalt pavement and recycled asphalt shingles. *Transportation Research Record, TRR,* pp. 1-11.

Merrill, D., Nunn, M. & Carswell, I., 2004. *A Guide to teh Use and Specification of Cold Recycled Materials for the Maintenance of Roads and Pavements,* s.l.: s.n.

Mhlongo, S., Abiola, O., Ndambuki, J. & Kupolati, W. K., 2014. *Use of Recycled Asphalt Materials for Sustainable Construction and Regabilitation of Roads.* Dubai, s.n.

Mivehchi, M., Wen, H., Wen, Y. & Wang, L., 2022. Study of measures to design asphalt mixes including high percentages of recycled asphalt pavement and recycled asphalt shingles. *Transportation Research Record, TRR,* pp. 1-11.

Moon, K. H., Falchetto, A. C., Wang, D. & Kim, Y. S., 2019. Experimental Investigation on Fatigue and Low Temperature Properties of Asphalt Mixtures Designed with Reclaimed Asphalt Pavement and Taconite Aggregate. *Transport Research Record (TRR),* Volume 2673(3), pp. 472-484.

Nantung, T., Ji, Y. & Shields, T., 2011. *Pavement Structural Evaluation and Design of Full-Depth Reclamation (FDR) Pavement.* s.l., s.n.

NAPA, 2021. *Asphalt Pavement Survey on Recycled Materials and Warm-Mix Asphalt Usage, 12th Annual Survey,* Greenbelt: NAPA.

NCHRP, 2011. *Recycling and Reclamation of Asphalt Pavements Using In-Place Methods, NCHRP Synthesis 421.,* s.l.: NCHRP.

Oke, O. L., 2013. Some Guidelines for the Production and Use of Cold Recycled Asphalt in Hot Tropical Regions. *International Jounal for Devlopement and Sustainability,* 2(2), pp. 998-1010.

Oke, O. L., O, A. J., Ogundipe, O. M. & Akinkurolere, O. O., 2013. Recycling of Asphalt Pavement for Accelerated and Sustainable Road Development in Nigeria. *International Journal of Scientific & Technology Research,* July.2(7).

Olson, Johnson, E. N. & C., R., 2009. *Best practices for RAP use based on field performance,* Mapplewood: Minnesota Department of Transportation.

Pavement Interactive, n.d. *Pavement Interactive.* [Online]
Available at: https://pavementinteractive.org/energy-and-road-construction-whats-the-mileage-of-roadway/ [Accessed 29 October 2022].

Pereira, P. A., Oliveira, J. R. & Picado-Santos, a. L. G., 2004. Mechanical Characterisation of Hot Mix Recycled Materials. *The International Journal of Pavement Engineering,* 5(4), pp. 211-220.

Pereira, P. & Picardo-Santos, L., 2006. *Technical - Economical Evaluation of Pavement Recycling Alternatives.* s.l., s.n.

Perez, I., Pasadin, A. & Medina, L., 2012. Hot Mix Asphalt using C&D aste as Coarse aggregate. *Materials and Design,* Issue 36, pp. 840-846.

Pinheiro, G., Vasconcelos, K. & Bernucci, L., 2022. Reclaimed Asphalt Pavemen Binder Extraction and Recovery evaluation and their effect on th Recycling Agenet Assessment. *Transport Research Record (TRR).*

Pradyumna, T. A., Abhishek & Jain, D. P., 2013. *Characterization of Reclaimed Asphalt Pavement (RAP) for Use in Bituminous Road Construction.* s.l., s.n.

Rafiq, W., 2020. Investigation on Humburg Wheel-Tracking device stripping perfromance properties of recycled hot-mix asphalt mixtures. *Materials.*

Rafiq, W. et al., 2021. Life cycle cost analysis comparison of hot mix asphalt reclaimed asphalt pavement: A case study. *Sustainability,* pp. 1-14.

Redelius, P. G., Lundberg, R., Thunell, L. & Otterstrom, O., 2012. *Long Term Pefromance of Cold Mix Asphalt.* Istanbul, s.n.

Saaty, 1990. How to make decision: The Analytic Hierarchy Process. *European Journal of Operational Research 48 (1990),* pp. 9-26.

Samir Magar, F. X. D. S. B. S., 2022. Applications of reclaimed asphalt pavement in India- A Review. *Journal of Cleaner Production* .

Setra, 2004. *Pavement Roadmixing and recycling of Bituminous Pavement Materials,* s.l.: s.n.

Sharma, A., Naga, G. R. R., Kumar, P. & Rai, P., 2022. Mix design development production and policies of recycled hot mix asphalt A review. *Science Direct.*

Sharmeny Mhlongo, O. A. J. N. W. K. K., 2014. *Use of Recycled Asphalt Materials for Sustainable Construction and Regabilitation of Roads.* Dubai, s.n.

Shirodkar, P. et al., 2011. A study to determine the degree of partial blending of reclaimed asphalt pavement binder for high RAP hot mix asphalt. *Construction and building materials,* pp. 150-155.

Shuler, S., Schmidt, C. & Golbaum, J., 2010. Life-Cycle Economic Performance for Hot Mix As[halt RehabilitationnStrategies. *Construction Education and Research,* pp. 152-162.

Shuling Tang, Y. C. a. J. F. L., 2012. *Structural Evaluation of Asphalt Pavements with Full-Depth Reclaimed Base,* s.l.: s.n.

Silva, H. M., Oliveira, J. R. & Jesus, C. M., 2012. Are totally rcycled hot mix asphalts sustainable alternative for road paving. *Resource conservation and recycling.*

Srinivasan, G., 2004. *Evaluation of indirect tensile strength to identify asphalt concrete rutting potential,* s.l.: West Vergina University.

Sullivan, J., 1996. *Pavement Recycling Executives Summary and Report,* Washington: s.n.

Susanne Chan et al., 2009. *Five Year Perfromance Review of Cold In-Place Recycling and Cold In-Place Recycling with Expanded Asphalt Mix on Highway 7, Perth, Ontario.* Vancouver, s.n.

Tang, S., Cao, Y. & Labouz, J. F., 2012. *Structural Evaluation of Asphalt Pavements with Full-Depth Reclaimed Base,* s.l.: s.n.

Tanzania Minstry of works, 2000. *Laboratory Testing Manual 2000.* s.l.:Tanzania Minstry of works.

Tebaldi et al., 2012. *Classification of recycled asphalt (RA) material.* s.l., HAL.

Timm H et al., 2021. Utilization of cold central plant recycled in Long-life flixble pavements. *Transportation Research Record, TRR,* 2675(11), pp. 1082-1092.

Tranfield et al., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Teview. Volume 14, pp. 207 - 222.

Ungureanu, D. et al., 2020. Accelerated testing of a recycled road structure made with reclaimed aspahlt pavement material. *Construction and building materials,* Volume 262, p. 16.

Veeraragavan, R. K. et al., 2017. Laboratory comparision of Rejuvinated 50% Reclaimed Asphalt Pavement Hot-mix asphalt with conventional 20% RAP mix. *Transport Research Record (TRR),* pp. 69-79.

Vorobieff, Wilmot, T. & George, 1997. *Is Road Recycling A Good Community Policy?.* s.l., s.n.

Wang, W. C. A., Yu, D., Liu, S. & Hou, W., 2019. Estabilishement and implementatio of an asphalt pavement recycling decision system based on the analytic Hierarchy process. *Resources, Conservation and Recycling,* pp. 738-749.

Wang, Y., Leng, Z., Li, X. & Hu, C., 2018. Cold recycling of reclaimed asphalt pavement twoards improved engineering perfromance. *Journal of Cleaner Production.*

Waqas Rafiq, M. A. M. M. A. M. N. M. H. S. W. S. A. M. F. J. a. A. M., 2021. Life cycle cost analysis comparison of hot mix asphalt reclaimed asphalt pavement: A case study. *Sustainability,* pp. 1-14.

Ware, Page-Green, P. & Charkes, 2006. some Materials and Construction Aspects Regarding in situ Recycling of Road Pavements in South Africa. *Road Materials and Pavement Design,* 7(3), pp. 273-287.

Weidong Cao, A. W. D. Y. S. L. W. H., 2019. Estabilishement and implementatio of an asphalt pavement recycling decision system based on the analytic Hierarchy process. *Resources, Conservation and Recycling,* pp. 738-749.

West, R. et al., 2009. Testing of Moderate and High Reclaimed Asphalt Pavement Content Mixes: Laboratory and Accelerated Field Perfromance Testing at the National Centre for Asphalt Technology Test Track. pp. 100-108.

Winkle, C. I. V., 2014. *Laboratoy and Field Evaluation of Hot Mix Asphalt with High Contents of Reclaimed Asphalt Pavement.* s.l.:s.n.

Wirtgen, 2012. *Cold Recycling Manual.* s.l.:s.n.

Writgen, 2010. *Writgen Cold Recycling Technology.* s.l.:s.n.

Yaning Qiao, E. D. T. P. O. V. L. M. G. N. Z. Y. a. Y. Z., 2019. Life cycle cost analysis of reclaimed asphalt pavement (RAP) under future climate. *Sustainability.*

Yinning Zhang, L. W. B. D. a. W. Z., 2016. Determining volumetric properties and permeability of asphalt-treated permeable base mixtures. *International journal of pavement engineering,* 17(4), pp. 343-352.

Zaumanis, Mallick & Frank, 2014. 100% recycled hot mix asphalt: A review and Analysis. *Resources. Conservation and Recycling,* pp. 231-244.

Zaumanis, M. & Mallick, R. B., 2015. Review of very high content Reclaimed Asphalt use in plant produced pavements: State of the art. *International Journal of Pavement Engineering,* 16(1), pp. 39-55.

Zaumanis, M. & Mallick, R. B., 2016. 100% Hot Mix Asphalt Recycling: Challenges and Benefits. *Elsevier,* pp. 3493-3502.

Zhang, Y., Wang, L., Diefenderfer, B. & Zhang, W., 2016. Determining volumetric properties and permeability of asphalt-treated permeable base mixtures. *International journal of pavement engineering,* 17(4), pp. 343-352.

Zhao, S., Shu, X., Huang, B. & Woods, M., 2013. Comparative evaluation of warm mix asphalt containing high percentage of reclaimed asphalt pavement. *Construction and building materials,* pp. 92-100.

Zhao, Y., Goulias, D. & Peterson, D., 2021. Recycled Asphalt Pavement Materials in Transport Pavement Infrastructure: Sustainability Analysis and Metrics. *Sustainability.*

Zhou, Z. et al., 2017. Cracking resistance characterization of asphalt concrete containing Reclaimed Aspahlt Pavement at intermediate temperatures. *Journal of Transportation Research Board,* pp. 46-57.

Appendix A: Publication

Endale, A. A., Ghataora, G. S. & Burrow, M. P. N., 2022. Asphalt pavement cold recycling and basic characteristics of RAP materials and their application. *Journal of Civil Engineering and Architecture,* pp. 38-51

Appendix B: Table showing List of Literatures Included in the systematic review process

		Quality Assessment						
It No.	**Literature/Study**	**A**	**B**	**C**	**D**	**E**	**Total**	**Focus area**
1	John, W. H., & David, J.K., 2009.	M	H	H	H	H	4.67	CIR
2	S. Khandal and B. Mallick, 1997.	H	H	H	H	M	4.67	General
3	Zumanis, M., Mallic, R.B., Frank, R., 2014.	M	H	H	M	H	4.34	CIR
4	Chen, D., 2006.	M	M	H	H	H	4.34	Cold plant and CIR
5	Shuling Tang, Yuejian Cao, and Joseph F. Labuz, 2012.	H	M	M	H	H	4.34	FDR
6	David A. Byrne, 2005	H	H	M	H	M	4.34	All / General
7	Jitareekul, P., 2009.	H	L	H	H	H	4.33	Hot recycling
8	Horvath, A., 2003	H	M	M	H	M	4.01	All / General
9	Gerardu, J.J.A. and Hendriks, C.F., 1985	H	M	M	H	M	4.01	All / General
10	Chen, D., & Jahren, C., 2007.	M	L	H	H	H	4.00	CIR
11	David Jones, Rongzong Wu, and Stefan Louw, 2015.	M	M	M	H	H	4.00	FDR
12	Diefenderfer, et al., 2016.	M	L	H	H	H	4.00	General
13	Thomas, J.K., et al., 1992.	M	L	H	H	H	4.00	General
14	Inhwan Kim, 2014.	H	M	M	H	M	4.00	Hot recycling
15	Pérez, I., Pasandin, A.R., Medina, 2012.	M	M	M	H	H	4.00	Hot recycling
16	NCHRP, 2011	H	H	M	H	L	4.00	Hot and cold inplace
17	Al-Qadi, Mustefa Elsiefi and Samuel H. Carpenter	H	H	M	H	L	4.00	All / General
18	Oke, O.L., Aribisala J.O., Ogundipe, O.M., Akinkurolere, O.O., 2013	H	H	M	H	L	4.00	All / General
19	Oke, O.L., 2010	H	H	M	H	L	4.00	All / General
20	Pereira, P.A. and Santos, L.P., 2006	H	H	M	H	L	4.00	All / General
21	Robert Karlsson, Ulf Isacsson, 2006.	M	M	M	H	M	3.68	General
22	TRB 2014	H	M	M	M	M	3.68	All / General

23	Scott Shuler Ph.D., P. E., Christopher Schmidt & Jay Goldbaum P. E. (2010)	M	M	M	H	M	3.68	Hot Recycling
24	Esenwa, et al., 2013.	M	L	M	H	H	3.67	CIR
25	Becca Lane and Tom Kazmierowski, 2012.	L	M	M	H	H	3.67	FDR
26	Brian K. Diefenderfer and Alex K. Apeagyei, 2011.	L	M	M	H	H	3.67	FDR
27	Clinton I.V.W., 2014.	M	L	H	H	M	3.67	FDR
28	Copland, A., 2011.	M	L	M	H	H	3.67	General
29	Holt, C., et al., 2009.	H	L	M	H	M	3.67	General
30	Mallela, H.L., et al., 2006.	L	M	M	H	H	3.67	General
31	Randy C. W., et al., 2009.	L	L	H	H	H	3.67	General
32	Robert, L., 2009.	L	L	H	H	H	3.67	General
33	Thomas, T. & Kadrmas, A., 2002.	M	L	M	H	H	3.67	General
34	Tom Wilmot and George Vorobief, 2009	M	H	M	H	L	3.67	All / General
35	Jhon Sullivan, 1992	M	H	L	H	M	3.67	All / General
36	Pereira, P.A., Oliveira, J.R. and Picado-Santos, L.G., 2004	M	L	H	M	M	3.35	Hot Recycling
37	Kamran Muzaffar Khan, et al., 2012.	M	L	M	H	M	3.34	CIR
38	Fujie Zhou & Cindy Estakhri, 2013.	M	L	M	M	H	3.34	FDR
39	Nantung, T.E., Ji, Y., & Shields, T., 2011.	M	L	M	M	H	3.34	FDR
40	Bocci, M., et al., 2014.	M	L	M	H	M	3.34	General
41	Per Gosta, et al., 2012.	M	L	M	H	M	3.34	General
42	Lee, J., Edil, T., Tinjum, J. and Benson, C., 2010	M	M	L	H	M	3.34	All / General
43	Carvalho, et al., 2010.	L	L	M	H	H	3.33	CIR
44	Praduman, T.A., et al, 2013.	L	L	M	H	H	3.33	CIR
45	Susan Chan, et al., 2009.	M	L	L	H	H	3.33	Cold Recycled
46	Wirtgen, 2012.	H	M	L	H	L	3.33	Cold Recycled
47	Kang-Won, W.L., & Muller, M., 2014.	H	L	L	H	M	3.33	General
48	Merrill, D., et al., 2004.	H	M	L	H	L	3.33	General

Appendix C: Questionnaires

1. Questionnaire used to develop Policy Framework

Dear Respondent,

Though Asphalt Pavement recycling technology is not new and its benefits of saving in materials and hence costs are well understood. However, it is not used in Ethiopia as might be expected. This may be because there are guiding principles or regulations that encourage and attract the practitioners and contractors to invest in such technologies. Thus, a questionnaire, which forms part of a research project on Recycling of Asphalt Pavement Technologies, that deals with deals with policy framework issues has been devised. See below. The purpose of this questionnaire is to assess whether policy is required, and if so, to devise a policy framework that can be used to encourage and guide the use of asphalt pavement recycling in Ethiopia.

This survey will take about 30miutes to complete

Your input in this survey is much appreciated. I should also just point out that there are likely to be a couple of other such surveys addressing different aspects of this project.

Thank you for your support

Alemayehu Ayele

Email: [redacted]

or

[redacted]

1 Do you have any experience in application of asphalt pavement recycling technology

Yes ○

No

If yes, please briefly describe the technology and its application. If possible, give references, web addresses where more details can be found.

_____

_____

_____

2 What is your view in applying asphalt pavement recycling in Ethiopia

Not a current importance (State why in the space provided)	○
It is expensive	○
May be used on major roads	
It is an important technology that can be applied right now	○

3 Do you think Asphalt pavement technology is attractive for developing countries, with respect to investment opportunities

Yes, it is attractive	○
Not attractive at all	○

4 Do you think asphalt pavement recycling can help in improving the environment

Yes,	○
No	○

In each case briefly state why

5 In Ethiopia asphalt pavement recycling is not commonly used, even where there is shortage of damping sites for removed existing pavement materials. Why do you think this is so? Please rank the reasons below from 1 to 5, while 5 is the likely cause and 1 is not likely. You can also add in the space provided your own cause and rank it similarly.

1	2	3	4	5

a. Lack of awareness of the environment impact	○	○	○	○	○
b. No available technology in Ethiopia to recycle	○	○	○	○	○
c. No regulation prohibits damping of removed materials	○	○	○	○	○
d. Lack of incentives for recycling of asphalt pavement	○	○	○	○	○
e. Lack of policy guidance on the use of Reclaimed Asphalt Pavement materials	○	○	○	○	○
f. Removed pavement materials are considered to be of poorer quality compared to virgin materials to justify investment on asphalt pavement materials	○	○	○	○	○
g. Lack of trained professionals in asphalt pavement recycling technology	○	○	○	○	○
h. Lack of specialized or experienced contractor who can use asphalt pavement recycling technology	○	○	○	○	○
i. Lack of awareness of the benefit of asphalt pavement recycling technology	○	○	○	○	○

_____

_____

_____

_____

6 How much of the AC pavements shall be recycled during rehabilitation and why?

	○
10%	○
20%	
	○
30%	○
40%	
50%	○
100%	○

Why?

_____

_____

_____

_____

7 Do you think asphalt pavement recycling shall be incentivized by the government

Yes ○

No ○

I don't know ○

In each case briefly explain why

_____

_____

_____

_____

8 If the answer to Q7 is "yes", which type of incentive do you think is most effective

i. Tax exemption on importation of recycling machineries ○

ii. Facilitate Loans for the contractor for purchase of recycling machineries and staff training ○

iii. Facilitate foreign currency for importation of Recycling machineries ○

iv. Extra addition of points during bid evaluation for those who propose the use of recycling of asphalt pavements on rehabilitation projects ○

v. Facilitation of land acquisition for installation of recycling plants (in case of hot and cold recycling in plants) ○

vi. Financial incentives for the use of recovered asphalt pavement materials from existing roadways

vii. Acknowledgment of the Recycling effort through Certificates ○

ix. Develop suitable standards to ensure quality recycled materials and pavement performance ○

9 Do you think economic Incentives will motivate to use recycled asphalt in road pavements?

Yes ○

No ○

I don't know ○

In each case briefly explain why

_____

_____

_____

_____

_____

10 Who should lead the initiatives of recycling?

Industry ○

Government (such as ERA) ○

Ministry of Transport ○

Ministry of construction ○

Body comprising representatives of all the above ○

11 Do you agree that asphalt pavement recycling contributes to road asset management

Yes ○

No ○

Don't know

If yes briefly describe what contribution it makes to road asset management

12 Do you think asphalt pavement recycling needs to be supported by policy framework?

Yes

No

I don't know

In each case briefly explain why

13 Do you think separate area should be setup for stockpiling recycled asphalt materials (RAP)

Yes

No

I don't know

In each case briefly explain why

14 Do we need to have a legal framework for recycling of Asphalt Pavements, and why?

Yes

No

I don't know

In each case briefly explain why

_____

_____

_____

_____

_____

15 Who do you think should implementer of Asphalt Pavement Recycling technology?



City Roads Authorities

Federal Roads Authorities

Regional roads Authorities

Ministry of Transport

Private contractors

Government owned road contractors

If you have any comments and suggestions, please use the space below

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

THANK YOU VERY MUCH!

2. Questionnaire used to develop Recycling selection method

Dear respondent his is part of a series of questionnaires in a research project on Recycling of Asphalt Pavement Technology. This part deals with evaluation of recycling technologies with respect to identifying ten (10) suitability measures. The purpose is to select most suitable recycling method that is applicable in developing countries.

Instruction:

You are required to give your score of the advantages obtained from a specific recycling technology on a rating scale of 1 to 4. If the recycling technology has the greatest advantage, then it will be scored 4, while if little or no advantage it will have a score of 1. Please put a cross mark "x" on your choice.

If you feel there is an important suitability measure that must be included, you can recommend and also rate it accordingly in the space provided at the end of the questionnaire. If you have additional comments or suggestions that may help in the process of selecting most applicable recycling technology, please include them in the space provided at the end.

We highly appreciate if you could complete and return your response before **30th of May 2017**.

We would like to thank you in advance for allocating your valuable time to fill in the questionnaire and send it back to us.

1	Evaluate Asphalt Pavement Recycling Technology in terms of "**Cost effectiveness"** on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				
	Full Depth Reclamation				
2	Evaluate Asphalt Pavement Recycling Technology in terms of "**Minimize Virgin Materials"** on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				

	Full Depth Reclamation				
3	Evaluate Asphalt Pavement Recycling Technology in terms of "**Economic Sustainability"** on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				
	Full Depth Reclamation				
4	Evaluate Asphalt Pavement Recycling Technology in terms of "**Environmental Sustainability"** on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				
	Full Depth Reclamation				
5	Evaluate Asphalt Pavement Recycling Technology in terms of "**Energy Saving"** on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				
	Full Depth Reclamation				
6	Evaluate Asphalt Pavement Recycling Technology in terms of "**Suitable for Low Volume Sealed Roads"** on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				
	Full Depth Reclamation				
7	Evaluate Asphalt Pavement Recycling Technology in terms of "**Suitability for Different Climatic Condition"** on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**

	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				
	Full Depth Reclamation				
8	Evaluate Asphalt Pavement Recycling Technology in terms of "**Ease of Construction"** on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				
	Full Depth Reclamation				
9	Evaluate Asphalt Pavement Recycling Technology in terms of "**Suitability for Small Scale Contractors"** on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				
	Full Depth Reclamation				
10	Evaluate Asphalt Pavement Recycling Technology in terms of "**Suitable for Labor Intensive Works"** on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				
	Full Depth Reclamation				
11	Evaluate Asphalt Pavement Recycling Technology in terms of "_____" on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				

	Hot In-Plant Recycling				
	Full Depth Reclamation				
12	Evaluate Asphalt Pavement Recycling Technology in terms of "_____" on a scale of 1 to 4 (1 is least advantageous and 4 is highly advantageous)				
		1	**2**	**3**	**4**
	Cold Planning				
	Cold-In-Place Recycling				
	Cold-In-Plant Recycling				
	Hot In-Place Recycling				
	Hot In-Plant Recycling				
	Full Depth Reclamation				

Comments/suggestions:

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Thank you!