ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

GRADUATE STUDIES

Laboratory Evaluation of Crushed Concrete Aggregate as Unbounded Base and HMA Surface Course

By: Tebarek Abdella

A thesis submitted to School of Graduate Studies of Addis Ababa University In Partial fulfillment of the requirements for the degree of masters of sciences

In

Civil Engineering

(Road & Transport Engineering)

Advisor Dr. Bikila Teklu

June 2018

Addis Ababa, Ethiopia

Addis Ababa University

Addis Ababa Institute of Technology

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DECLARATION

This research work has been done by the candidate himself and does not contain any materials extracted from elsewhere or from a work published by anybody else. The work for this thesis has not been presented elsewhere by the author for any degree or diploma.

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

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Ethiopia

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Lists of Acronyms

AASHTO- American Association of State Highways and Transportation Officials

ASTM- American Society for Testing and Materials

CCA- Crushed Concrete Aggregate

DBC- Design Bitumen Content

CDW- Construction and Demolition Waste

ERA- Ethiopian Road Authority

FHWA- Federal Highways Agency

GP- GS- Poorly Graded Gravel Sand mix

ITS- Indirect Tensile Strength

HMA- Hot Mix Asphalt

JMF- Job Mix Formula

JPCP- Jointed Plain Concrete Pavement

LL-Liquid Limit

MDD- Maximum Dry Density

MS- Manual Series

MTD- Maximum Theoretical Density

NA- Natural Aggregate

NCA- Natural Crushed Aggregate

OAC- Optimum Asphalt Content

OBC- Optimum Bitumen Content

PCC- Portland Cement Concrete

PI- Plasticity Index

RCA- Recycled Concrete Aggregate

TSR- Tensile Strength Ratio

USCS- Unified Soil Classification System

VFA- Void Filled with Asphalt

VMA- Void in Mineral Aggregate

VTM- Void in Total Mix

ABSTRACT

To diminish the adverse effects of construction and demolition wastes, this research investigated the physical and geotechnical properties of crushed concrete aggregate through intensive laboratory tests to evaluate as using for base course of flexible pavement and also laboratory tests were conducted for hot mix asphalt prepared and tested by Marshall mix design method with incorporation of crushed concrete aggregate to natural crushed aggregate in proportions of (0, 30, 50 & 100%). The volumetric properties of paving mixture investigated and optimum bitumen contents were determined for the different percent compositions of aggregate. Marshal flow & stability tests were conducted to know the performance of paving mixture. Performance test regarding moisture induced damage was conducted in laboratory since the absorption of crushed concrete aggregate was greater than the natural aggregate.

The physical property of crushed concrete aggregate indicates that CCA has lower specific gravity and higher absorption than natural crushed aggregate and it shows good resistance to Los Angeles Abrasion and static crushing load whereas the ten percent fines value reveals marginal quality. Voids (air void and voids in mineral aggregate), stability, flow & design bitumen contents increase as the percentage composition of CCA increase. Hot mix asphalt incorporated 30% & 50% CCA shows good performance against moisture induced damage. 100% CCA aggregate fulfill the requirements of base course (GB2 & GB3) as per ERA specifications. Finally a general method to evaluate the economics of utilizing crushed concrete aggregate is proposed.

Key Words; Crushed Concrete Aggregate, Base Course, Hot Mix Asphalt, Indirect Tensile Strength, Optimum bitumen Content.

CHAPTER 1- INTRODUCTION

1.0.Background

The growing population and the demand for improved and comfortable life style derive rapid expansion in urbanization which in turn requires immense infrastructures. The infrastructures desired by human being inquire eventual sophistication in design and construction. To this effect, construction materials are the entities which are gained naturally with direct exploitation. Gradually the irreversible natural resources are degraded on the contrary of the enhanced demand. Finding solution for this disastrous environmental depletion and for the unsatisfied demand requires comprehensive and integrated effort. Recycling of materials is considered as one of the solution for the mentioned problems. Since the material demand in construction is highly accelerated, recycling of construction and demolition wastes for multi-purpose importance is focused in this work.

Recycling of Construction and demolition wastes is alarmed when the environmental impact noticed and when scarcity is faced. Recycling of Portland cement started in Europe after World War II. With time and through necessity, recycled aggregates have become increasingly acceptable as road construction materials. Many countries also start to accept, regulate, specify and implement utilization of recycled concrete in their corresponding manuals. In recent years the use of Recycled Materials has been considered in road construction with great interest in many advanced industrialized and newly industrialized countries. Use of Recycled material in road construction applications is beneficial because it reduces the environmental impact and economic cost of quarrying operations, processing, conservation of landfills and transport (Rishikesh A. Khope & Milind V. Mohod 2015). Hence recycling concrete rubble and other construction demolition debris gives substantial sources of aggregate for utilization in a new construction of road and building.

Construction and demolition wastes will contain concrete, stone, bricks, ceramics, tiles, steel, wood and soils. Among the mentioned materials in construction and demolition wastes classifications can be made as recyclable and non-recyclable materials. The non -recyclable materials are land filled and incinerated whereas the recyclable material shall be investigated for their corresponding application areas. Construction and demolition wastes are generated from demolition of old structure, destruction of building and structures during earth quakes and wars, removal of useless concrete from structures, at construction of new buildings, waste concrete due to concrete cube and cylinder testing, demolition of curbing structures, pavement drainage structures and bridges, and demolition of old PCC pavements.

Our country, Ethiopia shows encouraging growth and attempt to transform into industrialized economic system. This transformation and economic development derives great demand for construction of infrastructures followed by the increased demand of construction materials. This growth also led to replacement of old infrastructures by the new construction. Due to this effect demolition wastes are highly increasing through time because of: right-of-way in urban and suburbs and demolition of curbing structures, new urban planning especially in the capital city and private economic growth to replace the old building with modern and high rising ones.

Developed country used to recycle concrete and other construction debris to reuse as hard standing, bank protection, fill and raising areas, for sub- base and embankment fills, noise barriers, backfill and under hard core fills without any processing. Many countries investigated in immense researches to use construction and demolition wastes as unbounded road bases and bitumen & cement bounded surface courses with partial replacement or with full potential. Those enhanced researches around the world on recycling of construction and demolition wastes are not only towards the monetary reward but also to greener environment and undisturbed ecosystems. Hence newly industrialized countries are also the stewardships for greener environment and shall consider conservation of their natural raw materials for the future by recycling to their utmost effort.

Ethiopia is one of the newly industrialized countries and this can be witnessed by observable enhancement of construction activities in the country and demolitions for the replacement of old buildings, rehabilitation of land uses and rehabilitation of urban streets. The flourishing construction activities are demanding more raw materials and the demolitions also cost more for landfilling. This unbalanced phenomenon can be regulated by considering recycling of construction and demolition wastes for reutilizing in different applications. Even though Utilizing construction and demolition wastes as road building materials is customary to developed countries there is no trials to use in Ethiopia except including the specification to use recycled asphalt pavement (RAP) in the national road authority manual.

Towards the glitches stated above and to gain the merits of recycling construction and demolition wastes researches should have to address this area to investigate the possible utilization of CDW's for conserving landfills which is very limited in the country, to realm the natural aggregate, to save energy and money. This research is the one which intends to add up some value to the recycling world by evaluating the properties of crushed concrete aggregate for utilization of asphalt wearing course and base courses in flexible pavement

1.1. Problem statement

Disposing of construction and demolition wastes has substantial adverse effects for the construction industry and as a whole for the natural environment. One of that is excess loading on landfills which are not sufficient for other non-recyclable materials. The other is not backing up of the natural aggregate which will be depleted through time due to the flourishing construction activities in the country and thirdly losing economic advantage from saving of disposal costs at landfills and transportation cost for rarely and far located landfills in the urban areas. Fuel and energy consumption at time of quarrying is also additional problem.

Utilizing construction and demolition materials for cheap application of earth fill, reinstatement of quarries & landscaping majorly affects the economic aspects of construction since for more expensive demands of applications as base course and as aggregate in hot mix asphalt can be considered.

1.2. Objectives

The general objective of this thesis is to evaluate the properties of crushed concrete aggregate in hot mix asphalt and to utilize as unbounded base course of flexible pavement. The specific objectives are:

i. To evaluate the physical and geotechnical properties of crushed concrete aggregate and compare the properties with natural crushed aggregate.
ii. To determine the performance of paving mixtures by conducting marshal stability flow tests for different proportions of RCA replacement to natural aggregate.

iii. To assess moisture induced damage of paving mixture incorporating crushed concrete aggregate in laboratory.
iv. To conduct the economic evaluation of utilizing crushed concrete aggregate.

1.3. Significance of the Research

This research will enlighten as how crushed concrete aggregate could be utilized for road construction. Recycling crushed concrete gives relief for environmental protection policy of the country and will give additional sources of aggregate for road construction. Therefore additional information will be provided for further investigation and formulation of policies on recycling of CDWs and to include in the specifications for the next amendment by the concerning road authorities and other stakeholders using this research as a mound.

1.4. Limitations of the research

This thesis explores the literatures about utilization of CDWs and conduct tests in laboratory that evaluate the physical and geotechnical properties of crushed concrete aggregate and conduct Marshall Mix design for dense graded hot mix asphalt by incorporating crushed concrete aggregate in different proportions to assess the volumetric and performance properties of the paving mixture. The properties are evaluated in according to ERA specifications for different applications. Chemical properties like: chemical composition and reactivity with other chemicals significantly influence the performance of the aggregate to be used in pavement layer. But this research did not explore those chemical properties due to in availability of testing apparatuses. In addition to this the performances of recycled concrete aggregates on site is not evaluated since there is no pavement constructed with recycled concrete aggregate.

CHAPTER 2- LITERATURE REVIEW

2.0. Overview of construction and demolition wastes

Construction and Demolition wastes (CDW) are produced during all stages in the life of a building(Kazal, 2015). Construction and demolition (C&D) debris is the waste material that results from the construction, renovation, or demolition of any structure, including buildings, roads, and bridges. Typical waste components include Portland cement concrete, asphalt concrete, wood, drywall, asphalt shingles, metal, cardboard, plastic, and soil (Ganiron, T.U. 2015)

Major prominent sources of construction & demolition wastes are: waste arising from the total or partial demolition of buildings and/or civil infrastructure, waste arising from the construction of buildings and/or civil infrastructure, soil, rocks and vegetation arising from land leveling, civil works and/or general foundations & road planning and associated materials arising from road maintenance activities. Among these waste materials, not all are advantageous and concern of recycling. Whereas cross contamination and general mixing of materials is frequently observed on construction and demolition sites. This is of greatest concern if the mixing involves hazardous materials.

This applies to materials such as asbestos and to certain heavy metals (such as lead), solvents and adhesives (Symonds, in association with ARGUS, 1999)

it is the major attention area to identify the composition of these waste materials in order to consider in recycling and re-using rather than to pull off and landfilled without any advantages and for adverse effects on environmental and economic aspects. Not only knowing the quantitative composition of the wastes led to decision for recycling but also their particular nature of the wastes in advance. To this regard wastes are classified broadly as recyclable and non-degradable (inert) based on the recycling concept. This broad classification in turn disintegrated by different category. According to report to DGXI, European Commission this classification of CDW is as follows: i) concrete, bricks, tiles, ceramics, and gypsum based materials; ii) wood; iii) glass; iv) plastic; v) asphalt, tar and tarred products; vi) metals (including their alloys); vii) soil and dredged spoil; viii) insulation materials; ix) mixed construction and demolition waste (Symonds, in association with ARGUS, 1999). Here in this research the main waste concerned among those types of wastes is **concrete** rubble from different sources for re-utilization as aggregate from the demolished concrete for road pavement construction.

2.1. Abundance of Construction and Demolition wastes

As many literatures revealed, rapid economic growth of the globe increased construction and demolition wastes significantly. The reasons for such increment are so many. For instance may be due to the objective of replacement of old structures with the new one, due to the right of way for expansion of new industries, roads and other infrastructures, due to new policy of urbanizations and so on (Sahay, A., & Saini, G., 2015) .

After world war-II the amount of construction and demolition waste increases abruptly due to the devastating effect of the war. Yet war is not the only cause for increment on the quantity of CDWs. Development of the country or institutional change from agrarian to industrialization makes the abundances in CDWs. Accordingly developed country now has generating multi million metric tons of construction and demolition wastes annually. For instance the Italian production of inert demolition materials amounted to approx. 35 million tons. (M. Cupo-Pagano et al.,1994) whereas statistics In Norway indicates that the approximate amount of construction and demolition waste generated yearly is 1.5 mill tons, (Petkovic, Engelsen, Håøya, & Breedveld, 2004; Aurstad, Aksnes, Dahlhaug, Berntsen, & Uthus, 2005). In the USA, over 130 million tons of Construction and Demolition (C&D) waste is produced each year. In Australia, more than 14 million tons of C&D waste was generated in 2004/2005 (Cameron, D. A., & Gabr, A. 2010). India at 2009 was generating construction and demolition (C &D) waste to the tune of 23.75 million tons annually (Yadav, S. R., & Pathak, S. R. 2009). In Netherland total amount of 14 Mton produced every year (Hendriks, 2016; Hendriks & Janssen, 2001). From the mentioned figures it can be observed that economically advanced countries generates enormous amount of construction and demolition wastes. Newly industrialized countries like Thailand, China, India, Malaysia, Sri-lanka and Vietnam generates substantial amount CDWs and increasing rapidly through time (Manowong & Brockmann, 2010).

Here in Ethiopia also substantial efforts are done to be industrialized country through the GTP (Growth & Transformation Plan). To this effect tremendous construction and demolition wastes are observed at present time and the abundance can be projected for the future. Even though there is no figurative fact sheets on the annual production of construction and demolition wastes one can be confidently witness as the quantity of construction and demolition wastes are increasing through time due to different policies of urbanization.

2.2. Utilization of Aggregates from CDW’s

Global production of construction and demolition waste has significantly increased over the last few decades, causing environmental problems due to its uncontrolled disposal. The use of recycled materials has been on the rise during the same period, primarily for the purpose of sustainable development and protecting the environment.

The main material included in CDW is the cement concrete from which, by application of appropriate recycling technologies, recycled aggregates result; they can successfully substitute crushed/quarry natural aggregates to the construction of rigid pavements, fresh concrete, and layers of flexible pavements (Kazal, 2015). The most widely used recycled materials are recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA). The aggregates in RAP are coated with asphalt cement that reduces the water absorption qualities of the material. In contrast, the aggregates in RCA are coated with a cementitious paste that increases the water absorption qualities of the material.

Thus the recycled aggregates can be utilized for reconstruction of building by casting as fresh concrete or as rigid pavement and/or as different layers of flexible pavements.

2.2.1. Recycled concrete aggregate for road construction

From the beginning of the concept of recycling construction and demolition wastes, aggregates from concrete rubble is used for road construction in flexible pavement either as earth fill or as layers above earth fill and in rigid pavement as concrete source. Here below some literatures are reviewed in this regards.

RCA for construction of flexible pavement

Flexible pavement contains different layers with lower quality at the bottom to better quality at the top. Recycled concrete aggregate is used for different layer construction of flexible pavement. It started from earth fill without requirement of any treatment to the surface layer with different treatments and extensive research works. Literatures collected from different sources conduct various experiments to utilize recycled concrete aggregate as unbound sub-base layer, as unbounded or bounded road base and as surface courses.

a) As unbounded Sub- base and Road base

Zaid Abdul-Zahra Mahdi, in his evaluation using crushed concrete aggregate as unbounded pavement layer, it is stated that recycling of waste concrete to obtain the recycled concrete aggregates (RCA) for base and/or sub-base materials in road construction is a foremost application to be promoted to gain economical and sustainable benefits (Mahdi, 2017).

In Britain, O'Mahony and Milligan studied the possibility of using crushed concrete and demolition debris as sub-base coarse aggregate. CBR experiments were conducted and the behavior of the recycled materials was compared with the behavior of lime-stone. The results showed that CBR of crushed concrete was similar to that of natural aggregate (O'Mahony, 1990). Conversely, demolition debris presented a fairly decrease in its CBR (Leite, Motta, Vasconcelos, & Bernucci, 2011).

Bennert et al. analyzed the performance of recycled concrete aggregate in base and sub-base applications. The authors concluded that a blended mixture of 25% of recycled concrete aggregate with 75% of natural aggregate would obtain the same resilient response and permanent deformation properties as a dense-graded aggregate base coarse, currently used in base and sub-base layers (Leite et al., 2011).

Molenaar and van Niekerk studied the influence of composition, gradation and degree of compaction on mechanical characteristics of crushed concrete and crushed masonry in the Netherlands. The results demonstrated that although the composition and gradation have an influence on the mechanical characteristics of the recycled materials, the degree of compaction is clearly the most important factor.

Substantial literatures assessed that recycled concrete aggregate can be used as sub-base and/or base course for different traffic levels. Among these literatures, Joralf Aurstad et.al evaluated mechanical properties versus field performance of unbound crushed concrete aggregate as a road building materials and concluded that Unbound crushed concrete aggregates seem to perform very well as base and sub-base materials, even on rather high volume roads (Aurstad et al., 2005).

In the studies of Narantuya Batmunkh et al. Sophisticated tests were conducted to investigate the mechanical responses of compacted crushed concrete subjected to applied loads simulated from traffic loads. Unconfined compressive strength, shear strength parameters and the resilient modulus of such material were determined. The findings of this tests showed that crushed concrete waste is able to be utilized as a road base material (Narantuya Batmunkh et al., 2007)

Durability is another factor to be investigated for full potential assessment of recycled concrete aggregate as sub base and base course layers. In this regard, Gordana Petkovic et al. conducted tests to assess freeze-thaw durability and degradation from water drainage and concluded that recycled concrete aggregate seems to have satisfying durability properties for the most common exposure conditions(Petkovic et al., 2004). Toughness is another parameter to measure the durability of recycled aggregate and this is done by Vahid Ayan et al. and concluded that the materials were appropriate for unbound sub-base for medium traffic in non-freezing condition from the standpoint of toughness. Also they are suitable for low traffic situations with low moisture and freezing weather (Ayan, Azadani, Omer, & Limbachiya, 2013).

The use of recycled concrete materials for capping and road sub-base can be economically advantageous when compared with the use of primary materials for the same purposes. Cost comparisons with primary aggregates suggest that savings of 20 - 30% are possible. These savings vary depending upon the geographical location and transport requirements(Symonds, in association with ARGUS, 1999).

In summary, the various literatures showed that it is possible to use recycled concrete aggregate for road construction as capping, sub-base and unbounded road base without any blending with natural aggregate and with some proportion to get better property. It is obvious that the common engineering properties to be fulfilled by natural aggregate as unbounded sub base and road base are satisfactorily fulfilled by recycled aggregate also. Even though the quality of the aggregates are satisfactory to use as sub base and/ or base course in road layer construction, some literatures reveal that cautions shall be taken for some unique properties like of absorption and degradation. Due to this and other factors to be considered, it is evident that there are differences in approaches to specifying RCA for unbound granular pavements. Undoubtedly State road authorities are influenced by experiences with natural aggregates and the origin of the rocks used to produce the aggregates.

b) Recycled concrete aggregate in bituminous mix

Recent researches focus on the advanced utilization of recycled concrete aggregate to surface courses and/ or bitumen bounded road bases. This gives more benefit since the aggregate required for this purpose had more quality than sub bases and other layers in pavement constructions. Here below some literatures are presented regarding of application of recycled concrete aggregate as bituminous pavement layers.

As stated by the research of M. Cupo-Pagano et al. experimental studies that makes it possible to consider using RCA for the manufacture of bitumen-treated base course with good mechanical strength characteristics were conducted. The results were satisfactory and allowed to state that a huge fraction of traditional aggregate may be replaced with recycled material. According to their opinion the examined material were satisfactory and allowed to point out the considerable savings in demolition waste exploitation, with greater advantages from the energy and environmental point of view (M. Cupo-Pagano et al., 2000).

With the scope of evaluating static and dynamic mechanical properties of mixtures containing Different percentages (0%, 15%, 30% & 50%) of Construction & Demolition materials, paper et al. concluded that C&D materials can conveniently be used in asphalt concrete for base layers (up to maximum 30%) without penalizing the mechanical performance of the mixture (Paper et al., 2014).

In another performance and other properties testing research work it is revealed that aggregate properties, volumetric properties of bitumen specimens containing RCA were relatively low compared to fresh aggregate properties, but the Marshall Stability value was higher for RCA compared to fresh aggregates with conventional bitumen and modified bitumen, the rutting deformation was higher for fresh aggregates compared to RCA. Some of these measured properties were within the acceptable limits, except the water absorption for 100% RCA, sample used in this study (Heeralal, 2009).

Another experimental studies conducted to use RCA in bituminous mixture exposed the strength variation of bituminous concrete surface course in which recycled aggregates are used in partial or full replacement of natural aggregates. Marshall's method is used to study the strength variations in bituminous concrete surface course with replacement of natural aggregates with recycled aggregates. It was found that replacement of natural aggregates by recycled aggregates up to 20% is possible in bituminous concrete surface course without significant impact on the strength characteristics. However there is an increase in the binder content for which there is a need to study the economic value of the replacement (Gurukanth, D, S, Vivek, & Naik, 2012). similarly the study accompanied with the aim of studying recycled construction and demolition waste aggregates to create hot asphalt mixtures for urban paved roads, concluded the use of construction and demolition waste aggregates in percentages of up to 20% for paving urban roads is feasible after conducting tests with four different proportion of replacement 10%-40% (Ossa, García, & Botero, 2016). Studies on moisture damage of recycled concrete aggregate done and the retained Marshall stability and tensile strength ratio are calculated by using two types of anti-stripping additives (hydrated lime and Portland cement). The results showed that both lime and cement could increase Marshall Stability, resilient modulus, tensile strength and resistance to moisture damage of mixtures especially at higher condition periods. Use of hydrated lime had better results than Portland cement(Behiry, 2013). Another article evaluates the possibility of designing hot asphalt mix road pavements using Construction and Demolition Waste as coarse recycled aggregates with the percentages of recycled aggregates used in the mixtures: 0%, 20%, 40% and 60%. Cement and lime were used as fillers. The mixtures made with coarse recycled aggregates complied with the Marshall technical specifications for low volume roads. The mixtures also showed good resistance to permanent deformation evaluated by means of wheel tracking tests. Nevertheless, the mixtures made with RA may have insufficient durability due to their high susceptibility to water action which was evaluated using stripping tests (Pérez, Pasandín, & Medina, 2012).

c) As Filler in HMA

Mineral fillers (cement & lime) and fillers from crushing dust are most widely used types in hot mix asphalt even if substantial investigations are conducted to replace those mineral fillers with fly ash, waste lime and cement by pass dust (Meizhu Chen, 2011). The major aim to add fillers is to maintain the excess air voids in the compacted mixture. Using crushed concrete as filler was investigated and found that crushed concrete aggregate powder can improve the properties of asphalt mixture, such as water sensitivity and fatigue resistance. But it may cause a little decrease of the low-temperature performance (Meizhu Chen, 2011).

However it can be summarized that recycled concrete aggregates (RCA) appear to be suitable materials to use in hot-mix asphalt (HMA) for flexible road pavements. However, the poor quality of RCA results in different engineering properties of an HMA using RCA compared to mixtures composed of natural aggregates. Varied laboratory results were obtained, likely because of the heterogeneous nature and origin of the RCA. Nevertheless, a majority of the studies report a high stripping of RCA mixtures. Several treatments help mitigate this problem. Some volumetric properties are discovered and the attached mortar arises many drawbacks not to use with full replacement of natural aggregate. Majorly absorptive property, moisture susceptibility, density, abrasive properties and change of gradation/fragmentation is adversely affect the mixture properties with increasing amount of recycled aggregate.

2.3. Merits of Recycling/Re-uses of concrete aggregate

Researches are conducted on recycling of aggregates from construction and demolition since there are multifaceted advantages. Among the advantages: environmental sustainability, economic benefits and saving of land fill areas are majorly raised as issue for recycling of aggregates. Several researchers have investigated the reuse of recycled materials for various civil engineering application purposes. Many barriers exist which prevent maximum utilization, particularly the recognition or acceptance of C&D materials in specifications and the need for research to demonstrate the suitability of recycled materials, as C&D materials have many economic, environmental, and social benefits. Sustainability Victoria (2009) state that the recycling industry is contributing to the environment by reducing greenhouse gas emissions and delivering significant energy, as well as preserving non-renewable virgin resources. In addition to this it creates an employment for the citizens (Sustainability Victoria, 2009).

2.3.1. Economic Merits

When economic merits are referred it meant only quantifiable parameters whereas, other intangible things will be seen in sustainability criteria. Donalson et al. (2011) performed a sustainability assessment of using RCA versus virgin limestone aggregate (VLA) in base courses from the perspective of environmental, social, and economic aspects. The environmental impact was found to demonstrate a reduced impact in favor of recycled concrete aggregate in process energy and disposal (viz. fuel used to haul concrete to landfill)

As per the report of FHWA State of the Practice National Review, the following economic advantages are stated as: Limit haul distance, Reduce disposal costs, Overall project savings, Minimize impacts to existing roads with reduced hauling ("Transportation Application of Recycled Concrete Aggregate FHWA," 2004).

Generally the literatures show that recycling of aggregates from concrete can be used for different applications like for pavement construction: flexible and rigid pavement and as new concrete aggregate with economical manner. Many economic tools are assed in various literatures with different aspect. Energy saving is one of the economic tools. Transportation cost saving is another parameter considered. Savings due to landfill preservation will engender another saving. Hence in addition to recycling of concrete aggregate gives multifaceted economic benefit against landfilling to waste.

2.3.2. Environmental sustainability of recycled concrete aggregate

The potential sustainability benefits associated with the use of these materials are many, including the preservation of natural resources, the reduced environmental impacts associated with both the production of new materials and the disposal of the RCWM (often expressed in terms of greenhouse gas emissions and energy consumption), and cost savings achieved by incorporating the recycled material(Dam & Dufalla, 2016).

The use of HMA made with RCA promotes sustainable construction by providing numerous environmental benefits, such as reduced extraction of natural aggregates from quarries, and avoidance of the visual impact of landfills, avoidance of rejection of raw materials. However, there are some disadvantages to the use of RCA in HMA. The cost of removal of impurities (e.g., gypsum) is one disadvantage. There are also environmental disadvantages, such as an increase in bitumen consumption with increasing RCA content and the associated increase in energy consumption. Limiting the RCA content to 30% produces a maximum increase of 0.5% in the bitumen content, which is an acceptable value (a. R. R. Pasandín & Pérez, 2013).

Another study done on comparison of quarrying primary aggregates and C&DW-derived aggregates done based on noise and dust suggested that for a specific volume of aggregates used in construction (including landscaping), quarrying primary aggregates and landfilling the equivalent volume of C&DW is less environmentally desirable than recycling the C&DW into C&DW-derived aggregates (Symonds, in association with ARGUS, 1999)..

On report of FHWA State of the Practice National Review, environmental advantages of recycled concrete aggregate are mentioned as: Resource Conservation, Conservation of virgin aggregate, Reduce impacts to the landscape, Metal recovery ("Transportation Application of Recycled Concrete Aggregate FHWA," 2004).

In summary it can be seen that recycled concrete aggregate gives infinite relief for environmental sustainability by preservation of the natural balance. This trend shall be promoted by considering such multidirectional merits. Many countries adopt and implement policies and regulations to encourage recycling of these inert materials for usable state for application in transportation infrastructures of specifically sub base, base course and surface courses in addition to PCC pavement application.

2.4. Recycling process of concrete aggregate

Recycling of concrete aggregate passes its own process. The difference with that of natural virgin aggregate processing for construction of infrastructures is due to availability of reinforcement. This reinforcement will be sorted out through different mechanisms either with magnetic separation or mechanical sorting. Sometimes double crushing will be required to acquire the desired quality level by reducing the amount of mortar. Henceforth literatures regarding the processing of crushed aggregate are reviewed here under.

2.4.1. Recycling process of Concrete aggregate

The steps for production of Crushed Concrete Aggregate (CCA) including: characterization of the source (existing building and/or concrete pavement), removal, crushing, sizing, and stockpile management (Dam & Dufalla, 2016)

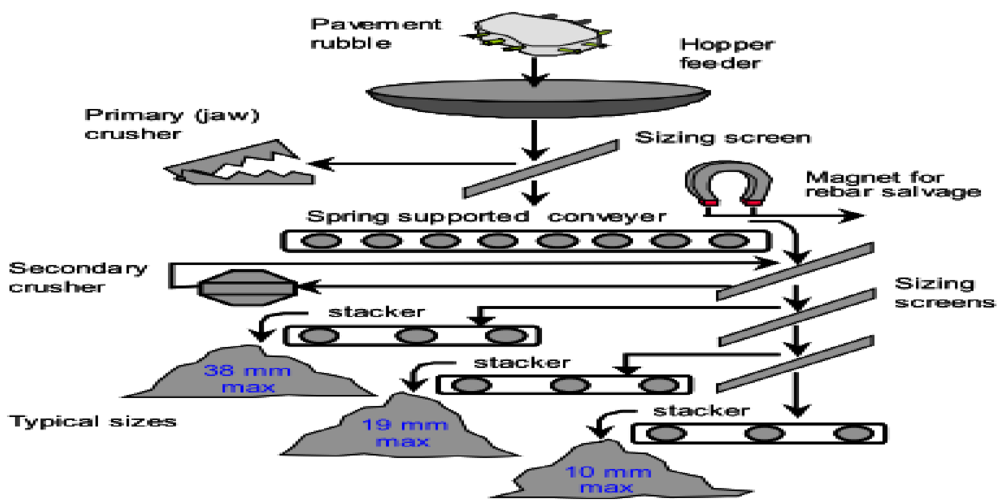

Fig 2. 1 Schematic illustration of crushing operations (Hoerner et al. 2001) Source (Applied Pavement Technology, 2011)

Fig 2. 2 Process of Waste Concrete Recycling (Ganiron, 2015)

Therefore from the literatures it can be observed that processing of recycled concrete aggregate is the same as natural aggregate. Their difference is mainly in sorting of metals and other impurities. This will be done with different methods as mentioned in the literatures above. In handling the stock of recycled aggregate the alkalinity staples and special treatments may be required in contrary to natural aggregate. The fine portion of recycled aggregate can be used as cement manufacturing entities and also for cement admixtures and soil stabilizers.

2.5. Unique properties of recycled concrete aggregate and their effects on performance of Hot Mix Asphalt

As every literatures referenced in this document indicates recycled concrete aggregate is different from natural virgin aggregate due to the attached mortar with the aggregate. This attached mortar affects many properties of the aggregate adversely and some properties impacted positively.

Literatures vis-à-vis properties of crushed concrete aggregate and the performance of the aggregates in hot mix asphalt will be seen here under.

2.5.1. Properties of aggregate:

Mortar content: CCA has a variable reclaimed mortar content that depends on the original concrete mixture proportions and crushing operations (Hiller et al. 2011). The volume of reclaimed mortar in the CCA also depends significantly on the original aggregate type. CCA processed from concrete originally made with rounded, less porous aggregates has less reclaimed mortar as the concrete tends to fracture at the aggregate-mortar interface during the crushing process. In contrast, more reclaimed mortar is often present if the original concrete was made with porous or crushed aggregates (Applied Pavement Technology, 2011) .

Usual mortar content is about 23-44% for 8/16 mm fraction and 33-55% for 4/8 mm fraction. Generally, amount of mortar attached to fine fraction is higher than to coarse fraction (Juan & Gutiérrez, 2004). The mechanical properties of the CCA whether used as an unbound base material or bound by cement or asphalt, are highly influenced by the volume of reclaimed mortar (Applied Pavement Technology, 2011).

Specific gravity: CCA particles generally have lower specific gravity values than natural materials, attributed to the reclaimed mortar bound to the CCA particles, which is less dense than most natural aggregates due to its porosity and entrained air structure (Snyder et al. 1994). Specific gravity has been observed to decrease as particle size decreases as reclaimed mortar content increases with reduced particle size (ACPA 2009) (Juan & Gutiérrez, 2004; a. R. R. Pasandín & Pérez, 2013; "Evaluation of Recycled Aggregates Test Section Performance Farhad Reza," 2017)

Absorption Capacity: when mortar content increases, water absorption increases too, especially in the finer fraction 4/8 mm. higher absorption is observed in crushed concrete aggregate due to the porosity of the attached mortar. This will affect the properties of moisture susceptibility of asphalt mix (a. R. R. Pasandín & Pérez, 2013; Behiry, 2013; Leite et al., 2011; A. R. Pasandín & Pérez, 2015; "Evaluation of Recycled Aggregates Test Section Performance Farhad Reza," 2017)

Particle Shape and Texture: The relative proportions of original coarse aggregate and mortar in CCA varies with the original concrete mixture design, the properties of the coarse aggregate particles (i.e., the angularity and surface texture, strength and elasticity), the bond between the natural aggregate particles and the mortar, and the type and extent of crushing used in production (ACPA 2009). Nevertheless, both coarse and fine CCA particles are highly angular and have rough surfaces, although the larger particles tend to contain greater proportions of reclaimed natural aggregate, whereas finer particles (those passing the No. 4 sieve) often are mainly crushed mortar (ACPA 2009; "Evaluation of Recycled Aggregates Test Section Performance Farhad Reza," 2017; Applied Pavement Technology, 2011)

Abrasion and Soundness: The 100% RCA met the Los Angeles (LA) wear requirement but failed the Washington degradation factor. Whereas the result of test conducted in Spain according to Spanish specification revealed that mixes of 0%, 5%, 10%, 20% and 30% replacement of natural aggregate by RCA, the combined (RCA + natural) LA abrasion coefficient complied with the PG-3 (LA < 25%) for HMA as a base course material in roads in heavy traffic category T00 (A. R. R. Pasandín & Pérez, 2013). Los Angeles abrasion loss percentage of recycled aggregate ranged from 35% to 42%. In Los Angeles abrasion test, all the attached mortar is removed, besides the abrasion suffered by natural aggregate (Juan & Gutiérrez, 2004). CCA will commonly fail the sodium sulfate test in ASTM C88 yet pass the magnesium sulfate test;

because of this discrepancy, it is not clear whether ASTM C88 is applicable to CCA materials and consequently many agencies waive these test requirements for CCA (ACPA 2009).

2.5.2. Properties of HMA using RCA

Asphalt content: as the literatures are reviewed by A.R. Pasandín &, I. Pérez, The majority of studies have stated that HMA using RCA have higher optimum asphalt contents (OAC) than conventional mixtures (Wong YD, et al.., 2007, Pérez I, et al. , 2007, Pérez I, et al., 2010, Pérez I, et al. , 2012 (Hsiao, Chong & Hsien, 2012; Shen D, Du J, 2004; Yoon-Ho, Taeyoung, Tai, Rak, 2011; Haifang & Bhusal, 2011; Bhusal et al., 2011; Rafi, Qadir, Ali, & Siddiqui, 2014) mainly because of the high porosity of the attached mortar (a. R. R. Pasandín & Pérez, 2013) Several typical findings, shown in Fig. 2.3, illustrate the relationship between the percentage of RCA and bitumen consumption. As seen in Fig. 2.3, the bitumen content increases with a higher RCA content. The OAC obtained by the different studies varies greatly. The different materials used (natural aggregates, RCA and fillers) could influence the asphalt consumption. Additionally, the mix design and use of treatments could affect the asphalt content. However, the national specifications of each country are the primary reason for different OAC for identical percentages of RCA.

Fig. 2.3 also indicates that the bitumen consumption is greater when the RCA is added in the fine fraction(Rafi et al., 2014) because of its greater mortar content (Juan & Gutiérrez, 2004) and larger specific surface area. For economic reasons, Bushal et al. proposed that RCA should be added to the coarse fraction to avoid high OAC.

Finally, Pérez et al. indicated that coating the particles present in RCA was difficult during the mixing process, particularly for siliceous particles and quartzite because of the chemical composition of these particles and the bitumen absorbed by the mortar. Additionally, the rough texture of RCA could introduce additional difficulties in the coating process. Thus, in addition to the high OAC content of HMA using RCA, some particles in the RCA are difficult to coat (Pérez et al., 2012).

Volumetric properties: HMA using RCA have higher air-voids contents (Va) than conventional mixtures (Paranavithana & Mohajerani, 2003; Pérez et al., 2012; Rafi et al., 2014). The Va could exceed 30% for RCA. Several authors stated that, generally, the percentage of air voids grow as the RCA percentage grows. Several authors attribute this variation in the air voids content to the high porosity of the attached mortar.

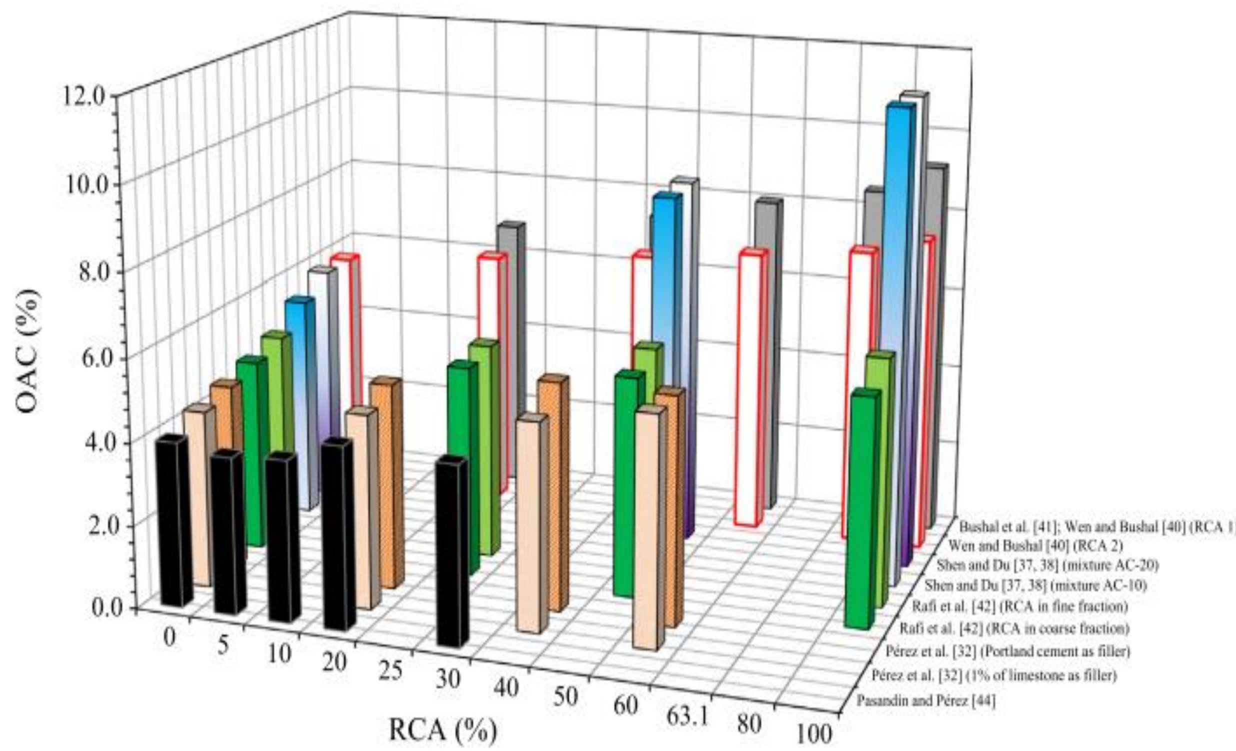

Fig 2. 3 Compiled optimum bitumen content of RCA (Pérez et al., 2012)

This high porosity is primarily responsible for the bitumen absorption of the RCA and, thus, the thinner bitumen film thickness; the thin film hinders the aggregate interlock after compaction (Pérez et al., 2012; A. R. Pasandín & Pérez, 2014; Pérez et al., 2012). However, this trend was not seen in all studies likely because of the design method used (for example some mix design methods indicate that a target air void content or a minimum film thickness must be reached) so the bitumen content increases as the percentage of RCA increases.

The RCA content also affects the voids in the mineral aggregate content (VMA) and the voids filled with asphalt content (VFA). Several authors indicate that as the percentage of the RCA increases, the VMA and VFA decrease (Bhusal & Wen, 2013). However, several authors reported a contrary trend, likely because the design method used increased the bitumen content. Several countries have specifications for the VFA. Therefore, some HMA made with RCA fail to reach the minimum VFA value established by national specifications (Paranavithana & Mohajerani, 2003).

Marshall flow and Marshall Stability: several authors stated that using RCA increases the Marshall stability of the mixture(Paranavithana & Mohajerani, 2003); however, other authors (Hsiao, Chong & Hsien, 2012; Shen D, Du J, 2004; Rafi et al., 2014) obtained the opposite result. Additionally, other studies indicate that the Marshall stability of mixtures with RCA is close to that of conventional mixtures (a. R. R. Pasandín & Pérez, 2013; Wu, Yang, & Xue, 2013). This lack of consensus could result from the fraction of RCA used. In this regard, Arabani and Azarhoosh and Arabani et al. indicated that using RCA as fines and filler increased the Marshall stability, whereas Zhu et al. indicated that employing RCA in both the course and fine fractions resulted in the lowest Marshall stability.

It is necessary to clarify two issues. On the one hand, some authors indicate that a certain value of natural aggregate replacement by RCA only complies with requirements (Rafi et al., 2014; M. Cupo-Pagano et al., 2000). This limit, which varies between 30% and 50% RCA, depends on the following factors: the nature of the virgin aggregate, the nature and origin of the RCA, the treatment used to improve the RCA properties and the type of mineral filler used. Therefore, with a proper selection of materials used to combine with the RCA (natural aggregate, mineral filler, and bitumen), the requirements for the Marshall stability should be met. On the other hand, several authors indicated that the Marshall criteria are met only for medium and low traffic. Additionally, several authors indicated that during the mixing and compaction process, the HMA using RCA suffers from changes in grain size distribution primarily because of the weakness of the attached mortar on the RCA surface. Cho et al. stated that using the Marshall mix-design method is insufficient in the manufacture of mixtures involving RCA. The primary reason provided by Cho et al. is that the loading during Marshall Compaction could break RCA course particles and, therefore, potentially underestimate the engineering properties of the HMA using RCA (A. R. Pasandín & Pérez, 2015).

Moisture damage resistance: various investigations indicate that the moisture damage resistance of bituminous mixtures with RCA varies. Thus, moisture damage resistance is a key aspect in the analysis of HMA using RCA and must be carefully studied to guarantee satisfactory durability and performance of such mixtures. The performance depends, among other factors, on the rate of replacement of the natural aggregate by RCA and the nature of both the RCA and natural aggregate. Additionally, the mineral filler has an important role in the success of the mixture. The nature of the RCA is affected by whether the material originates from structures formed exclusively by concrete (e.g., concrete pavements, bridge abutments, etc.) or from buildings, residences, or apartments. Likewise, the composition of the original aggregate (crushed or rounded, mineralogical composition, and texture) also influences the nature of the RCA.

several studies concluded that mixtures using RCA generally meet the national specifications for water resistance. Many of these studies qualify this finding by stating that the resistance to the action of water decreases with an increasing percentage of RCA; therefore, for percentages of RCA over 75%, the specifications are not met. Other studies indicated contrary results in which the water resistance results are far above the minimum required values.

CHAPTER 3- RESEARCH METHODOLOGY

The design of this research is experimental. Hence different laboratory experiments were conducted to know the quality of aggregates to utilize in hot mix asphalt and as base course. Mechanical strength tests of the aggregates were also done to know the bearing capacity of the aggregates if used for base course. Mainly hot mix asphalt were prepared and tested with different proportions of blending of crushed concrete aggregate and natural aggregate. In this chapter the summary of materials used and experimental procedures followed to develop the research is presented. Various types of materials are used like: crushed concrete aggregate, natural crushed aggregate and bitumen. The following portion describes the materials used and the test procedures referenced to ERA, ASTM, BS, Asphalt institute (MS-2 & MS-22), & AASHTO

3.1. Materials

Different materials were used in laboratory to achieve the goal of the research. Aggregates (crushed concrete aggregate and natural aggregate), bitumen as a binding agent and fillers from crushed concrete aggregate are listed and elaborated here under.

3.1.1. Crushed Concrete Aggregate (CCA/RCA)

The crushed concrete aggregate was collected from Addis Ababa University institute of technology compound in which one of the buildings was demolished. The reason for demolishing of the entire building was not investigated in this research but simply sample was collected. The sample collected was the one broken down in small size to pick easily by hand. The reinforcement was sorted and separated from the concrete for the superstructure part and the collected sample was free from any reinforcement. This sample was further crushed by asphalt aggregate crusher found behind bole airport and owned by Chinese company. The crushed aggregate was collected in three sizes ranging from: <6mm, [6, 13) mm, [13-19] mm. The nominal maximum aggregate size (which is one sieve larger than the first sieve to retain more than 10 percent) was 19mm. The maximum aggregate size (one sieve larger than the nominal maximum sieve) was 25mm. This sample was further quartered and prepared for the intended tests as per AASHTO T 2-91 (2000) / ASTM D 75 (2009) specification.

3.1.2. Natural Crushed Aggregate

The sample for Natural crushed aggregate was collected from Lidet consulting Engineers PLC, Which were submitted by anonymous contractor.

This natural crushed aggregate was used as a control mix without any incorporation of crushed concrete aggregate and used to blend with crushed concrete aggregate in different proportion to prepare HMA.

(a) (b)

(c) (d)

Fig. 3. 1Demolished site (a), (b) & (c) and collected demolished concrete (d)

3.1.3. Filler materials

Fillers are No. 200 (0.075mm) sieve size and the filler highly determines the properties of hot mix asphalt. Mineral fillers (cement & lime) and fillers from crushing dust are most widely used types in hot mix asphalt. For this research, crushed concrete aggregate was used as a filler since concrete contains cement and the literatures indicate that using crushed concrete aggregate as a filler can improve the properties of asphalt mixture, such as water sensitivity and fatigue resistance.

3.1.4. Bitumen

The Bitumen used for hot mix asphalt test was taken from the aforementioned consulting's laboratory. The bitumen quality tests were conducted to verify as the quality is under the specification limit of the inland and other commonly used manuals. The bitumen adopted for the research resolution was penetration grade of 80/100.

3.2. Aggregate Quality Tests

Prior to testing aggregates, the first procedure was to prepare the sample by quartering to get unbiased sample. Accordingly, as per AASHTO T 248-96 the crushed aggregate sample and the natural aggregate sample was quartered and prepared for the intended tests. Riffle box is available for quartering the sample and done with this apparatus.

(a) (b)

Fig. 3. 2 Quartered (a) and sieved (b) crushed concrete aggregate

3.2.1. Particle Size analysis

Since the aggregate from the crusher was delivered with three sizes, grain size analysis for each size was conducted as per AASHTO T 27-99 manual. Blending of these aggregates was done by trial and error to get the desired specification limit grading as per MS-2 and ERA flexible pavement design manual for base course and for hot mix asphalt requirements.

(a) (b) (c) (d)

Fig. 3. 3 Sieved crushed concrete (a, b & c) and natural aggregate (d)

3.2.2. Specific Gravity and Absorption

The specific gravity of each aggregate size (i.e. coarse, intermediate and fine) for both natural aggregate and crushed concrete aggregate is done as per AASHTO T 84 & AASHTO T 85 for fine and course aggregates respectively. In this definition fine aggregates are the aggregate size less than 4.75mm sieve size and coarse aggregates are greater than 4.75mm. This test was conducted for bulk specific gravity (dry and saturated surface dry) and apparent specific gravity. Usual procedures were followed to conduct the test for both fine and coarse aggregates.

3.2.3. Los Angeles Abrasion (LAA) Test

Los Angeles Abrasion is a measure of wearing/degradation capacity of the aggregate by revolving the aggregate in rounded steel container and impacted by steel balls. This test was conducted as per AASHTO T 96/ ASTM C131 test procedures. Since the nominal aggregate size was 19 mm, grading B was chosen for testing LAA.

3.2.4. Aggregate Crushing Value (ACV) Test

Aggregate crushing value was conducted as per BS 112 part 110, sample was prepared that passes 14mm sieve size and retain 10mm. About 4700gm sample was prepared and divided into two test specimens.

3.2.5. Ten Percent Fines Value (TFV) Test

Ten percent fines value test was conducted as per BS 812 part 111. The test principle is subjecting sample of aggregate to a load with free moving plunger and the aggregate is gone to crush. The crushed aggregate is sieved with 2.36mm sieve size and the mass is taken for the pass and retain to determine the ratio of the fine part to the coarser. This procedure is repeated with various loads to determine the maximum force which generates 10 percent of aggregate finer than 2.36mm sieve. This force is taken as ten percent fines value.

In this study for the soaked case done also with the same procedures except that the initial sample was soaked for 24hrs and after the crushed specimen has been removed from the cylinder dried in the oven at a temperature of 105 ± 5 °C to a minimum period of 12 h. The dried material was allowed to cool and weigh to the nearest gram

3.2.6. Atterberg Limits test

Liquid limit, plastic limit and plasticity index tests are performed according to AASHTO 88 & 89. Tests for liquid limit have two methods: Casagrande method and cone penetrometer method. In this study due to the unavailability of accessories for penetrometer, Casagrande apparatus was used even if more accurate data will be found with penetrometer test.

3.2.7. Moisture- Density Relationship Test

Moisture density relationship or proctor test was conducted as per AASHTO T 180-97 for crushed concrete aggregate only. This test has two versions: Standard and Modified one. For this study modified proctor test was conducted with 4.5 kg rammer and 457mm dropping height. Method C was followed by taking the material passing 19.0mm sieve and mould diameter 101.6mm.

The optimum moisture determined here was also used for CBR testing.

3.2.8. California Bearing Ratio (CBR) Test

This test was conducted to know the bearing capacity of crushed concrete aggregate at its optimum moisture and compaction. The test was conducted in accordance with AASTHO T 193-99. This test was conducted in order to evaluate the potential strength of the aggregate in terms of standard crushed aggregate having resistance of penetration 6.9mpa/2.54mm or 10.3mpa/5.08mm. The procedure followed in order to conduct the test is known as three point CBR determinations.

3.2.9. Chemical properties

The chemical properties of aggregates have to do with the molecular structure of the minerals in the aggregate particles. These properties are: Chemical composition and reaction with asphalt. Chemical composition assesses the mineralogical properties of the aggregate which is significantly influenced by the amount of cement of the original concrete. Mineralogical properties could be tested with X-Ray Diffraction (XRD), Chemical Micro analysis (EDS), and X-ray fluorescence (XRF) but for this research purpose those tests are not conducted due to unavailability of the technologies. But regarding to reactivity with asphalt, moisture induced damage is conducted in order to evaluate the chemical properties of the affinity of aggregate to asphalt molecules.

3.3. Bitumen Quality Tests

Bitumen quality tests were conducted to determine the specific properties of the bitumen used. Solubility in Trichloroethylene, Flash Point, Penetration at 25^{o}C, 100g, 5sec, Ductility at 25^{o}C, Penetration of residue percent of original, at 25^{o}c,100g, 5sec, Ductility of residue, at 25^{o}C, Softening Point & Specific gravity at 25^{o}C were determined. All the tests were conducted in accordance with AASHTO materials Test specification. No special procedures or considerations were taken for bitumen quality tests. Every test stated above was conducted in triplicate to get more precisions.

3.3.1. Solubility Test:

This test was conducted in accordance with AASHTO T 44. The principle for the test is to determine the solubility of asphalt in Trichloroethylene in which the portion that is soluble in Trichloroethylene represents the active cementing constituents. The method is summarized as: the asphalt sampled for this method was dissolved in trichloroethylene and filtered through filter mat and the insoluble material was washed, dried and weighted. Calculation was done as:

$$Soluble\ percent\ = 100 - \left(\frac{A}{B} * 100\right) ---------- (3.6)$$

Where: A- total mass of insoluble

B- total mass of sample

3.3.2. Flash Point Test

This test was conducted as per ASTM D 92-96 test procedures. The flash point of the sampled asphalt was determined by using Cleveland open apparatus. About 70ml of sample was taken and filled to the cup and raised the temperature by constant provision of flame around the cup using cylinder filled with oxygen gas. Thermometer was mounted to measure the temperature. The temperature was measured and recorded where some ignition of the asphalt was observed. And this temperature is recorded as flash point. The significance of this test was to know the flammability risk of the bitumen during mixing or handling.

3.3.3. Penetration Test

This test was conducted in accordance with ASTM D 5-95 test procedures. The penetration test is used as a measure of consistency. The naming of bitumen 80/100 is adopted from the value of penetration. This means the penetration value is in range of 80-100.

3.3.4. Ductility at 25^{o}C

The test procedures for ductility test were referred from AASHTO T 51-00/ASTM D 113-99. The test gives information about the tensile performance of bitumen.

3.3.5. Softening Point

Softening point test was conducted by following the procedures specified in AASHTO T 53-96/ ASTM D 36-95. This test was conducted to determine the melting point of bitumen in subject since the viscoelastic property does not allow determining the exact point of melting. Ball and ring apparatus was used to know the softening point. The setup of softening point test is shown below in fig. 3.6.

(a) (b)

Fig. 3. 4 ductility test specimen (a) & specimens under testing (b)

(a) (b)

Fig. 3. 5 ball and ring apparatus (a) Softening point under test (b)

3.4. Hot Mix Asphalt (HMA) Preparation and Tests

One of the aims of this study is to answer the question that crushed concrete aggregate could serve in hot mix asphalt as surface course of flexible pavement? Towards this goal many experimental studies had been conducted. 100% crushed concrete aggregate was used as aggregate in hot mix asphalt and the Marshall Mix design procedures were followed. Then additional mixes were prepared by blending crushed concrete aggregate with natural virgin aggregate with proportions of: 30:70%, 50:50% & 0:100% (CCA: NA). The percentage of composition is taken randomly and to deviate from some literatures which conduct the blending up to 40% and at 60% of crushed concrete aggregate. The procedures, the methods and methodologies followed in this course of actions are described below.

3.4.1. Aggregate Blending and Sample Preparation

As it is mentioned earlier that aggregates from crushing site was delivered in three different sizes (<6, [6-13), [13-19). The qualities of the aggregates were tested and no refrain from usage according to specifications were found. Hence the aggregates were blended in order to attain the gradation limit of fullers 0.45 power chart. The blending were done on excel spreadsheet with trial and error method. Even though weight was taken for each sieve size, in order to determine the weight of each sieve size blending was mandatory task. The Marshall Mix design was done for dense graded bitumen by using Fullers 0.45 gradation chart which looks like as shown below. Blending of different size aggregates was done to attain the design gradation curve as much as to resemble the maximum density curve and to be in the limit of upper and lower gradation curves.

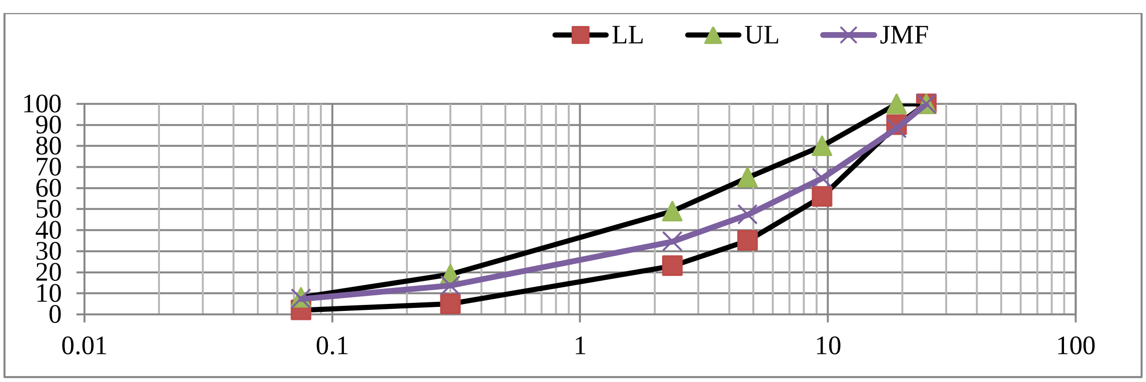

Fig. 3. 6 Fullers 0.45 power gradation, upper & lower limits of ERA specification

3.4.2. Mixing and Compaction

Trial mix was prepared to determine the weight which will fit the height of mould 63.5mm. This trial mix was very tall with 1200gm aggregate which was used for natural aggregate approximate weight.

The weights of aggregates for each sieve size was determined from gradation envelop and weighted for each sieve size. Aggregates were prepared for five different bitumen contents having two specimens for each bitumen contents.

The mix design was prepared following the right procedures specified and prescribed in ERA flexible pavement design manual and Asphalt Institute Manual Series (MS-2) except the number of specimens to be prepared for one bitumen content is reduced from three to two. For this study case in order to be economical and the variation in mean value is not significant.

(a) (b)

Fig. 3. 7 aggregate and mixing tools heating (a) & pouring of bitumen to aggregate (b)

The compactions of the specimens were done with automated equipment by adjusting number of blows 75 by assumption for heavy traffic. The specimens were compacted 75 blows in each side. The compacted specimens were allowed to cool at ambient temperature and extracted for further tests of bulk specific gravity and Marshall Stability flow test.

(a) (b)

Fig. 3.8 mixing (a) and pouring to mould for compaction (b)

3.4.3. Tests for Volumetric Analysis

Marshall Mix design was developed majorly for determining the volumetric properties of hot mix asphalt and strength tests (i.e. Marshall Stability and flow). In order to determine the volumetric properties the parameters to be determined with laboratory testing are specific gravities (bulk specific gravity and maximum theoretical specific gravity).

Fig. 3. 9 compacting machine setup

i) Determination of bulk specific gravity

The compacted specimens were properly labeled and extracted after sufficient cooling.

Weights for each specimen for dry condition were recorded. This test was conducted as per AASHTO T 166/ASTM D 2726-93 a standard test method for bulk specific gravity and density of compacted bituminous mixtures using saturated surface dry specimen.

ii) Determination of Maximum Theoretical Density (MTD)

This is also density measuring parameter to determine the air void which in turn used to determine level of compaction of hot mix asphalt. Theoretical maximum density was conducted in accordance with ASTM D 2041. This test was conducted for un-compacted lose state mixture and also checked from the compacted mixture since literatures state that the gradation change during mixing also affect the value of maximum theoretical density. But in this research no significant difference was observed.

(a) (b)

Fig. 3. 10 soaked (a) and dry (b) specimens after compaction

iii) Marshall Stability and Flow Tests

After bulk specific gravities of the test specimens had been determined, stability and flow tests were performed. Procedures to Marshall Stability and flow test were as follows: The prepared specimens were immersed in water bath constantly maintained to 60^0C for 30min. The testing head for automatic machine was also kept at the same temperature by putting in the bath for a while. Since the testing machine was automatic and digital every readings including the graphs for stress strain was displayed on the screen. Fig 3.13 below shows the setup of testing apparatus.

(a) (b)

Fig. 3. 6 Sample preparation in loose state (a)& from compacted sample (b) for Maximum Specific Gravity

Fig. 3. 12 Vacuum application for saturated sample

3.4.4. Volumetric Analysis

Volumetric analysis of hot mix asphalt was done in order to know the degree of compaction and to determine the optimum bitumen content. Void in total mix (Air Void), Void in mineral aggregate (VMA), Void filled with asphalt (VFA) & effective asphalt content (Pbe) was determined through analytical approach from the specific gravities determined via test. The methodology for calculation of each parameter is discussed below.

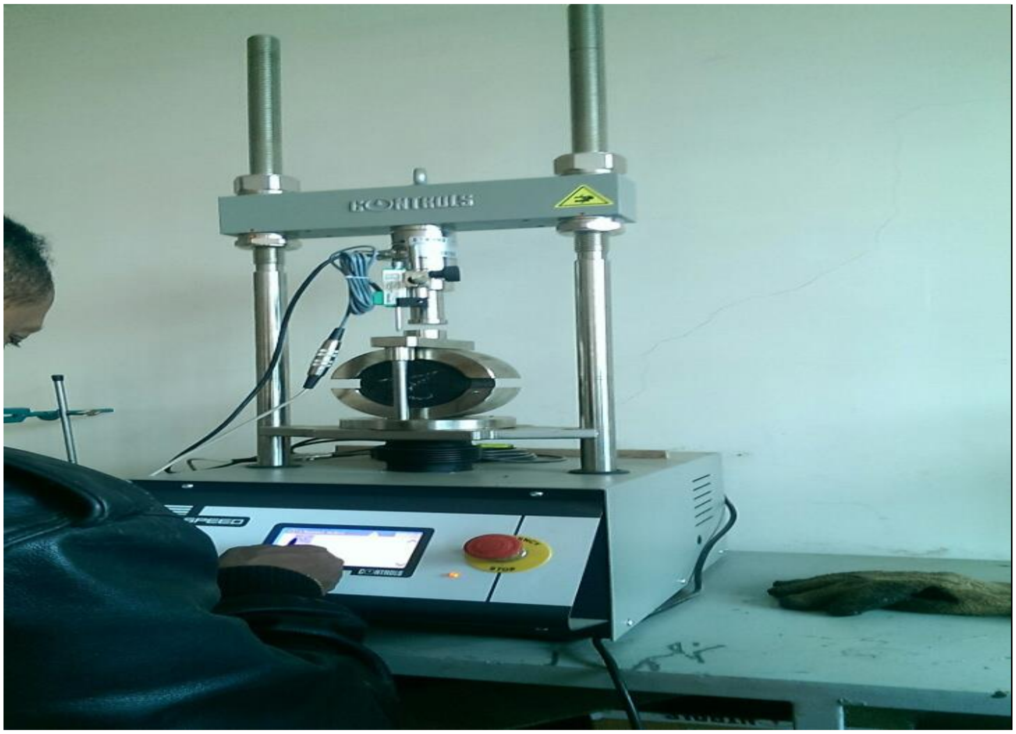

Fig. 3. 7 Marshall Test apparatus setup & test in progress.

i) Air Void (Va)

The air void in compacted mixture dictates the percent of compaction and the available space for future compaction. From this result future service life of the HMA pavement could be predicted and other void parameters could be calculated. The air void in percent was determined to find other volumetric parameters and to evaluate the specification limit ERA flexible pavement design manual.

ii) Voids in Mineral Aggregate (VMA)

It is the inter-granular void space between the aggregate particles in the compacted paving mixture that includes the air void and the effective asphalt content expressed in percent of the total volume.

iii) Voids filled with Asphalt (VFA)

VFA is the percentage of the inter-granular void space between the aggregate particles that is filled with asphalt. VFA does not include the absorbed asphalt.

iv) Effective Asphalt Content (Pbe)

The effective asphalt content P_{be} in the paving mixture is the total asphalt content minus asphalt quantity absorbed by the aggregates. Effective asphalt content governs the performance of asphalt paving mixture. The effective bitumen content for the paving mixture prepared in laboratory for this research is calculated and presented in the next chapter.

3.5. Determination of Optimum Bitumen Content

Principally The objectives for Marshall Mix design of HMA are:

- to have sufficient asphalt in the mix to endure durable pavement,
- to get a mix with adequate stability to satisfy the demands of traffic without distortion or displacement,
- to have voids content high enough to allow for a slight amount of compaction under traffic loadings without flushing, bleeding and loss of stability, yet low enough to keep out harmful air & moisture.
- Sufficient workability to permit efficient placement of the paving mixture without segregation.

Accordingly to achieve the objectives mentioned above the bitumen content optimization is the sole solution.

The bitumen content in this research was determined as per Asphalt Institute MS-2 and with NAPA (National Asphalt Pavement Association) method and compared the values from both methods and the bitumen content which satisfies all the criteria was adopted.

Formerly analyzed values were plotted in graph of best fits plot in excel spreadsheet. The plot includes: Stability vs. Bitumen Content, Flow vs. Bitumen Content, Unit weight of total mix vs. Bitumen Content, Percent air voids vs. Bitumen Content, Percent VMA vs. Bitumen Content & Percent VFA vs. Bitumen Content

After plotting of the points for each various bitumen contents, two methods were followed to determine the maximum bitumen content.

Method 1: bitumen content at 5% of air void was determined and this bitumen content was checked for the other parameters whether the specification requirement is fulfilled or not.

Method 2: bitumen content at maximum stability, bitumen content at 5% air void and bitumen content at maximum density was determined and the values of the three bitumen content was averaged. This bitumen content was evaluated for other voids, stability and flow parameters whether the specifications requirements are satisfied or not. The bitumen content from the two methods was compared. The minimum among the two values were the one computed with method 2, but this bitumen content does not fulfill the requirement of air voids and VFA. Hence bitumen content determined from method 1 (at 5% air void) was adopted as optimum bitumen content.

3.6. Indirect Tensile Strength Test (ITS)

This test was conducted to determine the potential damage of hot mix asphalt due to moisture induced damage. This test is not customary in our country even specifications are provided in the manual. Crushed concrete aggregate is highly absorptive, when the hot mix asphalt with this type of aggregate is exposed to moisture, stripping will be occurred (i.e. the bitumen will detach from the aggregate and water will intrude to the compacted mix and the mix will be prone to moisture damage. ITS test was conducted to measure the performance of the mix that will show on site when exposed to the severe condition.

ITS test was conducted in accordance with AASHTO T 283-89(1993) resistance of compacted bituminous mixture to moisture induced damage. Generally the test covers preparation of specimens and measurement of the change of diametric tensile strength resulted from the effects of saturation and accelerated water conditioning of compacted bituminous mixtures in laboratory. The result was used to predict the long term stripping susceptibility of bituminous mixtures.

(a) (b)

Fig. 3. 8 dry and conditioned specimens (a) and fractured faces after testing (b).

Fig. 3. 9 ITS testing setup.

CHAPTER 4- RESULTS & DISCUSSION

The laboratory test results of physical and geotechnical properties & properties in hot mix asphalt for crushed concrete aggregate, natural crushed aggregates and their combinations are presented and discussed in this portion. Laboratory tests conducted which include: physical & geotechnical properties of aggregates such as: grain size analysis, particle density & Absorption, Atterberg limits, Los Angeles Abrasion, Aggregate Crushing value, Ten percent fines value Moisture density relationship & California bearing ratio tests. Marshall Mix design for different proportions of CCA and NCA was also conducted. Furthermore tensile strength test were conducted to predict the moisture induced damage of the compacted paving mixture.

4.1. Physical Properties

The physical properties of crushed concrete aggregate collected from compound of Addis Ababa Institute of technology demolished building which was crushed by asphalt crusher of the Chinese company and the natural crushed aggregate which was collected from Lidet Consulting Engineers Plc. was tested in laboratory of Lidet Consulting Engineers laboratory are discussed here:

4.1.1. Particle Size Analysis

The result of particle size analysis from sieve analysis for CCA is shown in fig 4.1 below. In fig 4.1 the line “LL” is the curve for lower limit specification for base course (GB1) as per ERA specification and “UL” for upper limit. As shown in figure the gradation of the aggregate fall in specification limit. In the lower bound of the left side (finer sieve sizes) it looks to deviate from lower bound. That means the material in analysis seems coarser but the compaction effort will change the gradation to finer since the attached mortar on the aggregate goes to crush. It was found that the change in gradation of aggregates containing RCA, as coarse aggregates, due to the effect of mixing and compaction is significantly higher than that for fresh basalt aggregate (Paranavithana & Mohajerani, 2003).

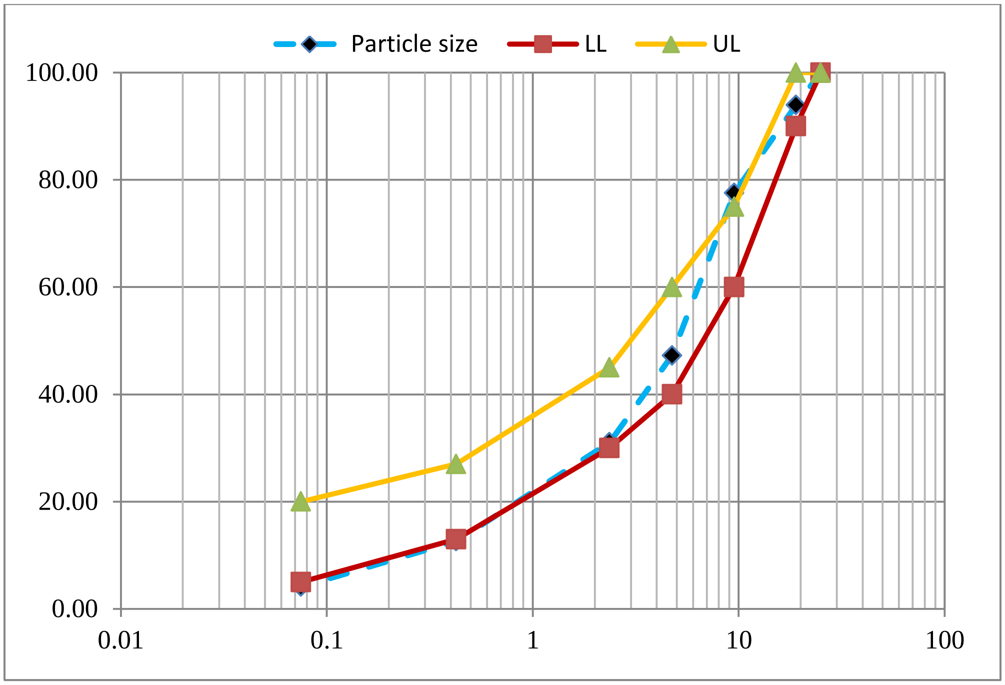

Fig. 4. 1Particle Size distribution for crushed concrete aggregate

Based on grain size analysis the aggregate can be classified as poorly graded gravel, gravel sand mix according to the unified soil classification system (USCS). The gravel/coarse, sand/intermediate and fine percentages are 47.2%, 43.8%, and 9.0% respectively. The calculated coefficient of uniformity (C u) and coefficient of curvature (Cc) values are 16.99 and 3.19, respectively. Coefficient of uniformity Cu is a basic shape parameter to define the grain size distribution and coefficient of curvature Cc is also used along with Cu (Holtz and Kovacs, 1981). Coefficient of uniformity Cu and coefficient of curvature Cc are calculated from the following equations.

$$Cu = \frac{D60}{D10} ---------4.1$$

$$Cc = \frac{D302}{D60 * D10} ------4.2$$

Where: D_{60}, D_{30} & D_{10} are the sieve size that passes 60%, 30% & 10% respectively.

The results for the grain analysis are shown in table 4.1 :

Table 4. 1 Particle size distribution of RCA samples

Physical Properties of RCA	
D 10 (mm)	0.32
D 30 (mm)	2.33
D 60 (mm)	5.37
Coefficient of uniformity (Cu)	16.99
Coefficient of curvature (Cc)	3.19
Gravel content (%)	47.20
Sand content (%)	43.80
Fine content (%)	9.00
USCS classification	GP-GS
AASHTO classification	A-1-a

Gradation is not a limitation even if the specification requirement regarding the gradation does not fulfilled because the gradation could be adjusted by blending with other aggregate to gain the required gradation limits. More concern shall be given for other properties of the aggregate.

4.1.2. Specific gravity and Absorption

All of the literatures around recycled concrete aggregate revealed that the specific gravity of the RCA is lower than convectional aggregate due to the porosity of the mortar attached to the aggregate. The absorption on the contrary is higher than the natural aggregate. This is also due to the attached mortar on the surface of the aggregate. The results of the specific gravities and absorption for crushed concrete and natural aggregate are summarized in table 4.2- 4.5.

As it can be observed from the results the absorption of fine aggregate in crushed concrete aggregate is greater than coarse aggregate. This indicates that more mortar is found in the fine portion. The specific gravity in fine CCA is also less than coarse CCA as it was indicated by the literatures.

Table 4. 2 result for specific gravity of CCA

Particle size	Average Specific gravity		
	Bulk (dry)	Bulk (SSD)	Apparent
Fine	2.00	2.21	2.54
Coarse	2.26	2.42	2.71

Table 4. 3 result for absorption of CCA

Particle size	Average Absorption (%)	Standard Specification (%)
Fine	8.85	< 2.00
Coarse	7.48	< 2.00

Table 4. 4 Test result for specific gravity of NCA

Average Bulk Specific gravity(SSD)	
Fine	2.80
Coarse	2.73

Table 4. 5 Test result for Absorption of natural crushed aggregate

Particle size	Average Absorption (%)	Standard Specification (%)
Fine	1.87	< 2.00
Coarse	1.15	< 2.00

When comparison is done between the crushed concrete aggregate and natural aggregate in terms of specific gravity, the specific gravity of natural aggregate is much greater than the specific gravity of crushed concrete aggregate. This is due to the presence of light weight mortar in CCA. On the contrary the absorption of CCA is greater than the absorption value of natural aggregate. This is again due to the porosity of mortar which is the cause for deficient properties of such kinds of aggregates.

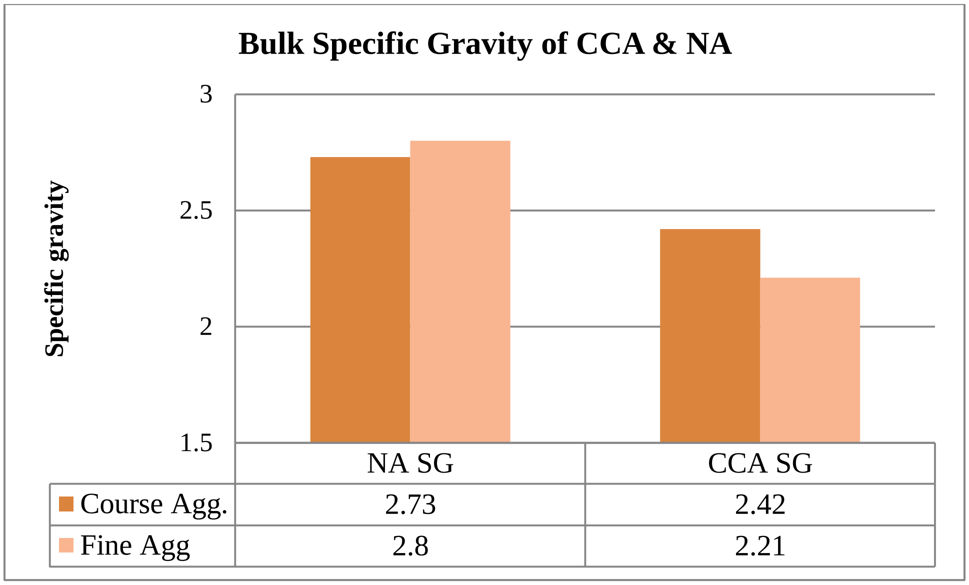

Fig. 4. 2 Specific gravity result for CCA & NA

The limit of specification for maximum absorption as per ERA specification for utilizing the aggregates in hot mix asphalt is 2%. But the result of the tested aggregate deviate much more than the specification. This indicates that utilizing crushed concrete aggregate in hot mix asphalt on more water occurring area will cause stripping problem. Yet this will be tested later with tensile strength test by exposing the compacted paving mixture to water soaking in laboratory. Hence it is not recommendable to use 100% CCA in hot mix asphalt without any treatment.

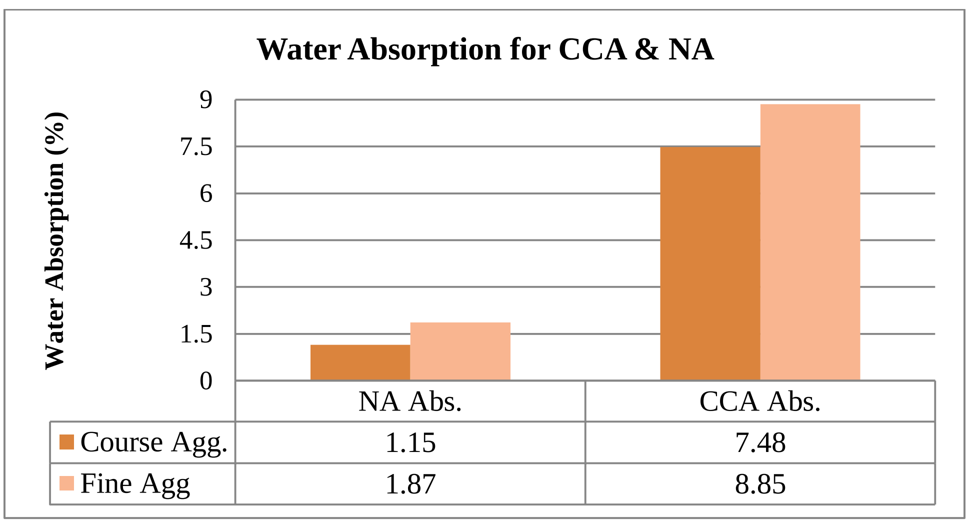

Fig. 4. 3 Water absorption for NA & CCA

4.1.3. Los Angeles Abrasion Value

The mechanical wearing capacity of the aggregate tested by Los Angeles Abrasion exhibit that the crushed concrete aggregate is good against abrasion. The specification of ERA sets the maximum value of LAA **29** for unbounded base course (GB1) and 30 for bitumen/ cement bounded wearing surface. Here the result shows that crushed concrete aggregate satisfy the requirement in terms of LAA for both base course and aggregate for hot mix asphalt wearing course.

Table 4. 6 Los Angeles Abrasion (LAA) result for crushed concrete & natural aggregate

	CCA	**NA**	**Standard Specification**		**Remark**
Average LAA (%)	27.0	15.0	< 29 for base course	< 30 for asphalt aggregate	both types of aggregates are under specification limit

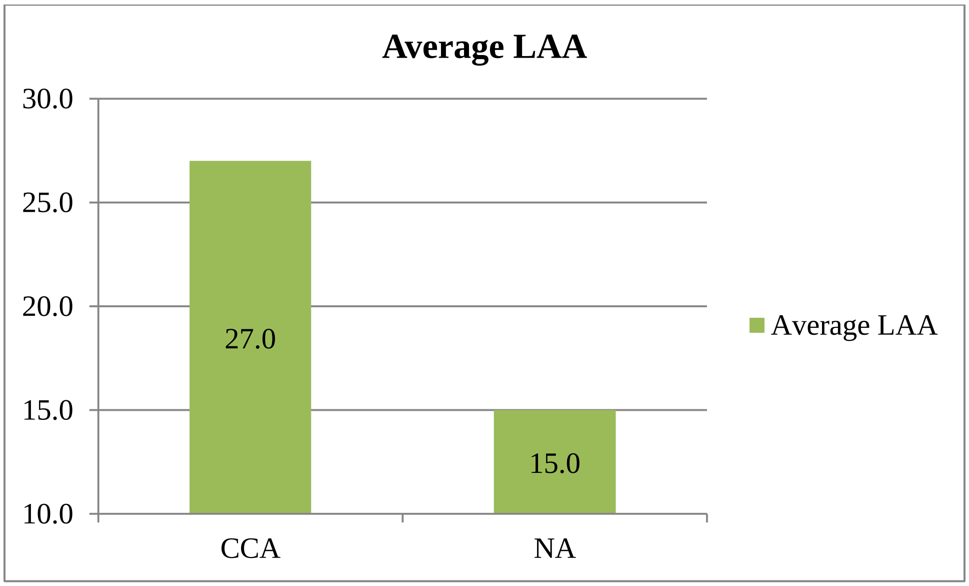

Fig. 4. 4 Los Angeles Abrasion values for CCA & NA

	CCA	**NA**	**Standard Specification**		Remark
Average LAA (%)	27.0	15.0	< 35 for base course	< 30 for asphalt aggregate	both types of aggregates are under specification limit

Even if the natural aggregate unveil much better value than the crushed concrete as expected, the crushed concrete aggregate also has a quality against abrasion with in specification limit.

4.1.4. Aggregate Crushing Value (ACV) test

Aggregate crushing value (ACV) can be used as a quality control test for base course and hot mix asphalt aggregate according to ERA specification. Due to this ACV was conducted for both crushed concrete aggregate and natural aggregate to compare both values and to check whether the value of ACV is with in specification limit or not. Accordingly the result for this test is presented in table 4.7.

Table 4. 7 Aggregate Crushing Value (ACV) for CCA & NA

	NA	**CCA**	**Standard Specification for base course**	**Standard Specification Asphalt Aggregate**	**Remark**
Average ACV (%)	14.0	25.9	< 29	< 25	Both aggregate types are with in specification limit for base course & CCA is out of limit for Asphalt Agg.

It is expected that natural aggregate has more resistance than crushed concrete aggregate for static impact load. Yet the crushed concrete aggregate unveil good property against the static impact load.

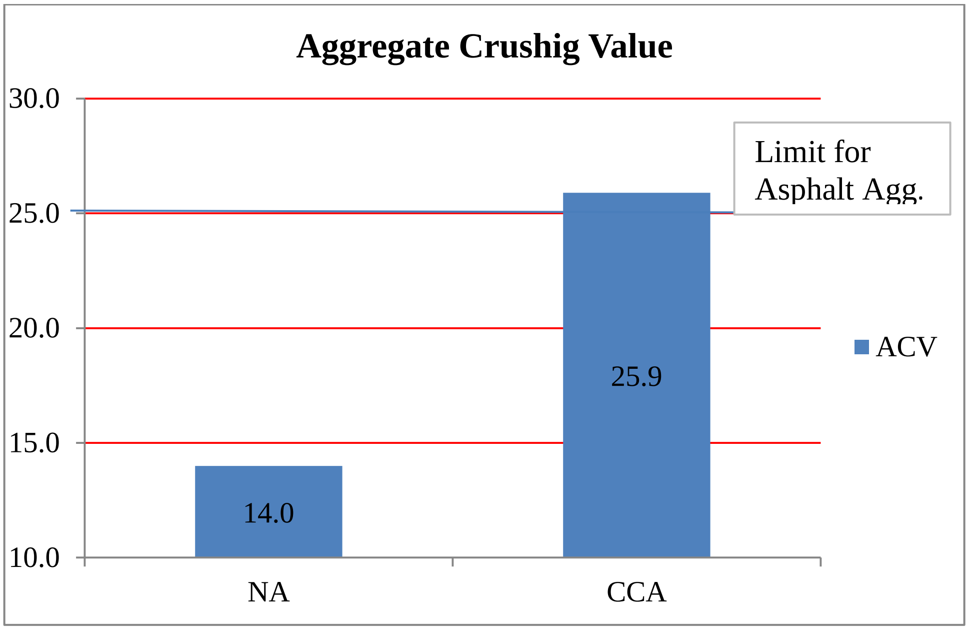

Fig. 4. 5 Aggregate Crushing Value for CCA & NA

4.1.5. Ten percent Fines Value (TFV) Test

The strength and durability requirements of crushed stone shall be assessed using the 10% Fines Aggregate Crushing Test (10% FACT), in terms of the dry and wet strength, and the wet/dry ratio related to rock type are specified in ERA specification. In this specification the general requirement for most of rock type is 110KN.

Table 4. 8 Ten Percent FACT result for CCA

TFV(Ten percent Fines value(KN)		Specification for base course	Specifications for Asphalt Aggregate
Dry condition	110	>110	> 160
Wet condition	92	-	-
Ratio (wet/dry)(%)	84	> 75	> 75

Table 4. 9 Ten Percent FACT result for Natural Aggregate

TFV(Ten percent Fines value(KN)		Specification for base course	Specifications for Asphalt Aggregate
Dry condition	290	>110	> 160
Wet condition	280	-	-
Ratio (wet/dry)(%)	97	> 75	> 75

This result reveals that crushed concrete aggregate fulfills the minimum requirement for base course in dry condition but does not satisfy for the requirement of aggregate in hot mix asphalt which is greater than 160 KN. The result indicates that the durability of the bituminous mix will be in doubt if 100% CCA is used in pavement construction. As expected from the literatures reviewed, CCA has lower TFV than natural crushed aggregate.

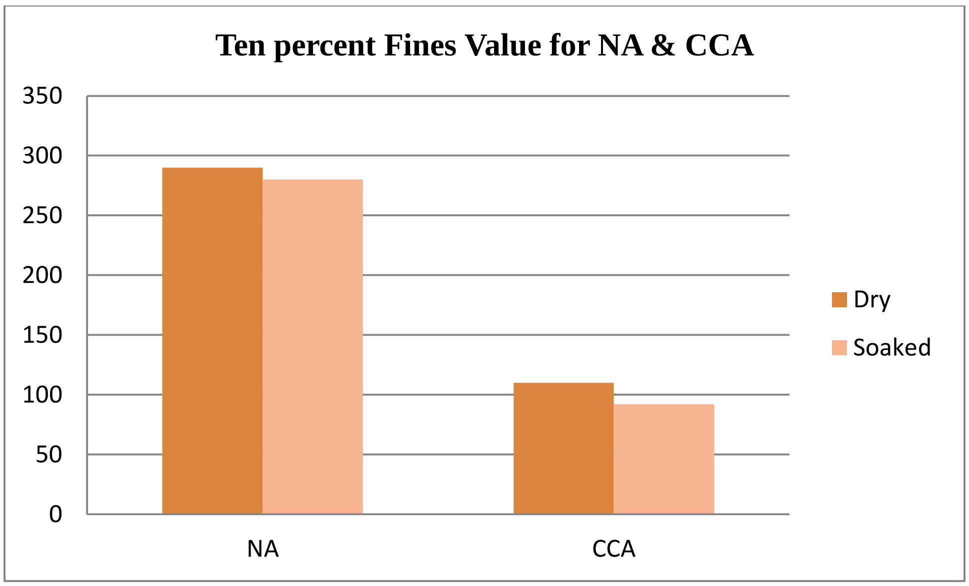

Fig. 4. 6 Ten percent Fines Value of NA and CCA

4.1.6. Atterberg limits

The Atterberg limit is directly related to clay mineralogy and as such, higher clay contents result in higher plasticity. However, CCA is made of crushed stone, cement and sand, hence the clay contents in CCA materials is very low. Therefore, the plastic limit and liquid limit of the RCA samples could not be obtained. Hence it can be taken as non-plastic

(NP). Being NP is the desired quality for base course (GB1) and for hot mix asphalt aggregate according to ERA and MS-2 specifications.

4.2. Geotechnical properties

Majorly proctor test and CBR tests were conducted to know the geotechnical properties of the aggregates. Compaction/proctor/ moisture- density relationship test was conducted to know the maximum dry density and optimum moisture content and California bearing ratio test to determine the bearing capacity.

4.2.1. Compaction test

Compaction test is used to determine the optimum moisture content to attain the maximum dry density. This moisture content also used to prepare specimens for CBR test. The validity of this test is to check level of compaction on site at a time of construction. The proctor test for CCA conducted gives the result shown in fig. 4.7.

From the figure it could be observed that the optimum moisture content (OMC) of the crushed concrete aggregate is **13.6%** and the maximum dry density at this moisture content is **1.938** (1938 Kg/m^3). The maximum dry density is much lower than the natural aggregate. Whereas gradation adjustment can increase the maximum dry density (mahdi, 2017) This moisture content is used for preparation of CBR specimens.

4.2.2. California Bearing Ratio (CBR) test

California bearing ratio (CBR) is used as a major strength measuring tool for unbounded pavement layers. Accordingly the test for the CCA was conducted and the result is shown in fig. 4.8.

The CBR test result taken at 95% of MDD is 85%. Some literatures stated that the CBR of crushed concrete is more than natural aggregate (Aurstad, Aksnes, Dahlhaug, Berntsen, & Uthus, 2005; Hassoon and Obaidi,2014) .Whereas (O'Mahony, 1990) states that recycled concrete aggregate has similar result to that of natural aggregate. The cementing effect mentioned on (AASHTO, 1993) will be the factors for the increment of CBR value in CCA.

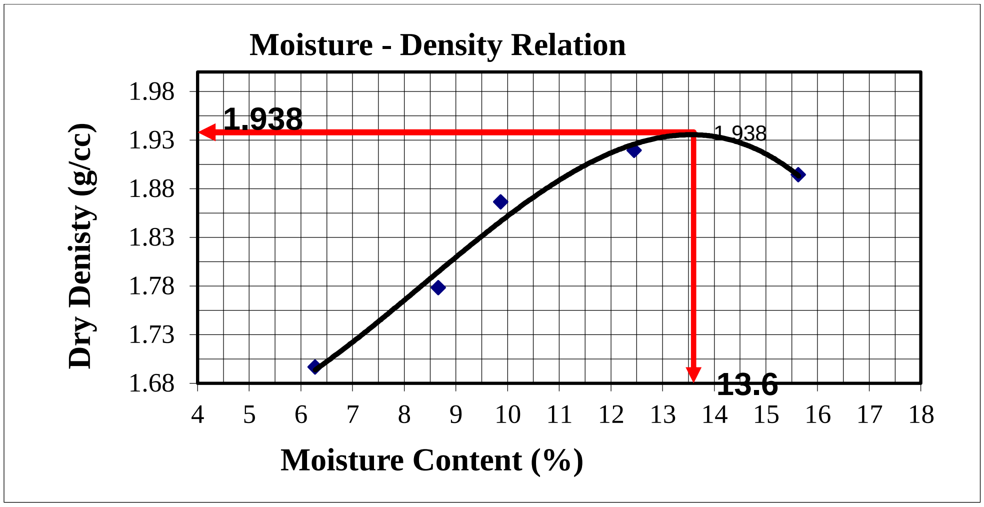

Fig. 4. 7 Moisture density relationship graph

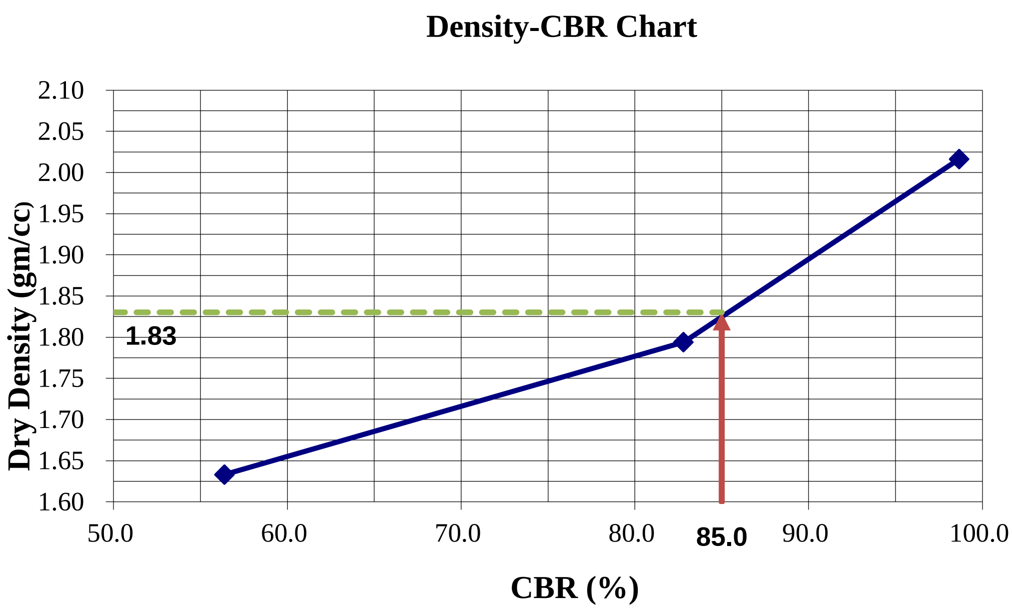

Fig. 4. 8 CBR vs. MDD graph

Here in this research the result shows lower value than natural crushed aggregate but in acceptable range of base course (GB2 & GB3) specification which is >80%. The researcher's opinion is that the CBR for the CCA shall be conducted after curing since the anhydrate cement will create a bond between materials and will increase the value of CBR. Hence it meant that crushed concrete aggregate can utilize for unbounded base course (GB2 & GB3) construction without mentioning strength problem.

Table 4. 10 Summary of aggregate quality test results with corresponding ERA specification

Item No.	Test type		Material type		Specification for base course GB1	Specification for asphalt agg.
			CCA	NCA		
1	ACV (%)		25.9	14	**Max 29**	**Max 25**
2	TFV	Wet (KN)	92	280	**-**	**-**
3		Dry (KN)	110	290	**Min 110**	**Min 160**
4		Ratio (%)	83	97	**Min 75**	
5	LAA (%)		27	15	**Max 35**	**Max 30**
6	Specific gravity(Bulk)		2.13	2.80	**NA**	**NA**
7	Absorption (%)		8.17	1.51	**NA**	**Max 2**
8	PI		NP	NP	**NP**	**NP**
9	MDD (Kg/m^3		1.938	NA	**NA**	**NA**
10	OMC (%)		13.6	NA	**NA**	**NA**
11	CBR (%)		85	NA	**100$^+$**	**NA**

NA: Not Available, NP: Non Plastic (PI=0)

In summary the results for physical and mechanical properties of crushed concrete aggregate shows good quality to utilize as unbounded road base materials as per ERA specification. The crushed concrete aggregate can be used as GB2 & GB3 without any modifications and will be used as GB1 if the bearing capacity will increase with curing time by modification of gradation. To increase the CBR value, the RCA needs the lowest amount of materials that is less than the sieve size (0.075) mm (mahdi, 2017). Another method like submerging, washing and drying them has a positive effect on the performance of CCA, considerably reducing their water absorption and their specific gravity (Pourtahmasb, S. M., 2016).

The mechanical and physical properties of crushed concrete aggregate also shows good quality to utilize as asphalt aggregate except the absorption property and the durability problem which were evaluated by TFV and ACV. The Los Angles Abrasion value shows conformance with the specification of ERA.

4.3. Bitumen Quality Test Results

From the test results it can be deduced that the bitumen has good quality and can be used in hot mix asphalt. Regarding to this deduction the bitumen was used in marshal mix design for preparation of test specimens.

Table 4. 11 Summary of test results for all bitumen quality tests

Item No.	AASHTO T 44 Solubility in Trichloro ethylene, (%)	AASHTO T 48 Flash Point, ^{O}C	AASHTO T 49 Penetration at 25^{o}C, 100g, 5sec	AASHTO T 51 Ductility at 25^{o}C (cm)	Penetration of residue percent of original, at 25^{o}c,100g, 5sec	AASHTO T 53 Softening Point (^{0}C)	AASHTO T 228-06 Specific gravity at 25^{o}C (kg/m^{3})
1	99.9	298.0	88.0	100^{+}	90.0	43.2	1016.0
2	99.9	298.0	89.0	100^{+}	90.0	43.8	1016.0
3	99.9	300.0	89.0	100^{+}	90.0	43.4	1016.0
Average	99.9	298.7	88.7	100^{+}	90.0	43.5	1016.0
Standard Specification	> 99.0	> 219.0	80 ~ 100	> 75	> 50	42 ~ 51	NA

4.4. Marshall Mix Design

Marshall mix design was conducted to retort the questions on the research whether crushed concrete aggregate serve as aggregate in hot mix asphalt or not. If yes what are the unique properties and how it affects the nature of paving mixture. Could it be used by itself only or need blending with natural aggregate to optimize the mixture characteristics, if it requires natural aggregate, how much replacement will give better mix property? How is the trend when the proportion of crushed concrete aggregate is increased in replacing the natural aggregate? Hereafter in response towards those and other questions Marshall mix design was conducted for proportions of aggregate (0:100, 30:100, 50:50 & 100:0) of CCA: RCA. In Marshall Mix design there are analytical procedures and tests for the analysis in order to determine the optimum bitumen content and to check the volumetric properties as if are in specification limit to be followed. These analytical processes in the delivery of the results and test results are presented and discussed below.

4.4.1. Aggregate and bitumen quality check

Quality Tests for both types of aggregate (i.e. crushed concrete aggregate and natural aggregate) as presented above revealed that both types of aggregate can be used as hot mix asphalt except the crushed concrete aggregate fails to meet the requirement for 10% FACT. Bitumen quality tests also unveil that the bitumen can be used in hot mix asphalt. Accordingly the process continued to aggregate gradation adjustment.

4.4.2. Design of aggregate grading

Aggregates with different sizes provided was blended to the proportion that falls in the specification limit and resembles to the maximum gradation curves. This proportion was conducted with trial and error method to accomplish the desired gradation curves. The result of this design for both natural aggregate and crushed concrete aggregate is shown in the figures 4.9 & 4.10

In laboratory it is possible to prepare aggregates with this maximum gradation curve because weight is taken for each individual size. But in actual site it is impossible to manipulate the gradation designed in laboratory. Hence the proportion from coarse (10-20), intermediate (5-10) & fine (0-5) delivered from actual crushing site was proportioned with the ratio of (40%, 17% & 43%) of the coarse, intermediate and fine aggregates respectively. the blending and the sieve size analysis is shown in appendix.

The gradation curve seen here indicates more fine value (closer to upper limit) for larger sieve sizes and coarser to smaller sieve size. This will give the advantage to tolerate change of gradation during compaction and mixing since crushed concrete aggregate especially the fine portion is more vulnerable to this effect than natural aggregate (Sumeda Paranavithana & Abbas Mohajerani,2013).

This gradation curve was designed also based on the trial mixes prepared prior to main mix design which shows higher air void than the coarser gradation curve. Figure 4.10 presented the gradation design for natural aggregate. The design for this curve is also done with trial proportion of (32%, 27%, and 41%) coarse, intermediate and fine aggregates respectively.

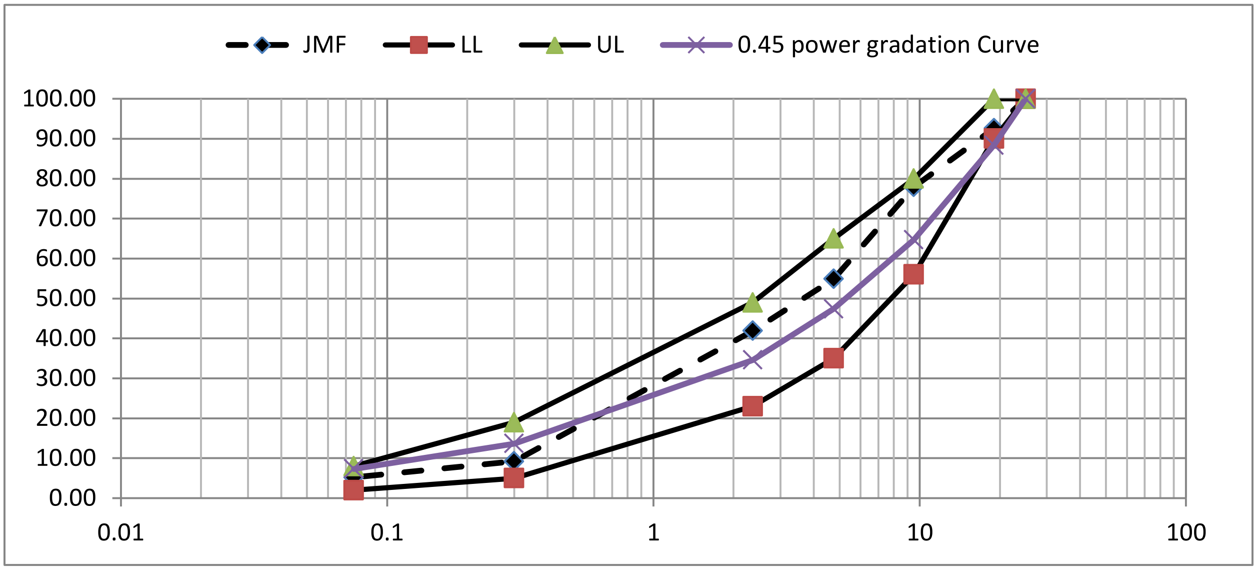

Fig. 4. 9 Gradation curve for Crushed concrete aggregate

4.4.3. Determination of bitumen content (ASTM-D 3515)

The initial design bitumen content was found from the formula;

$$DBC = 0.035a + 0.045b + Kc + F - - - - - - - (4.3)$$

Where:

a = Percent of aggregate retained the 2.36 mm sieve

b = Percent of aggregate passing the 2.36 mm sieve and retained on 0.075 mm sieve

c = Percent of aggregate passing the 0.075 mm sieve

K = 0.15 for 11-15% passing 0.075 mm sieve, 0.18 for 6-10% passing 0.075 mm sieve, and 0.20 for 5% or less passing 0.075 mm sieve.

However the bitumen content for crushed concrete aggregate was 6.44 ~**6.5** by taking F=2, but this number was the initial and the design bitumen content for natural aggregate was **5.1** by considering F=0.7, but in actual sense these values are significantly different.

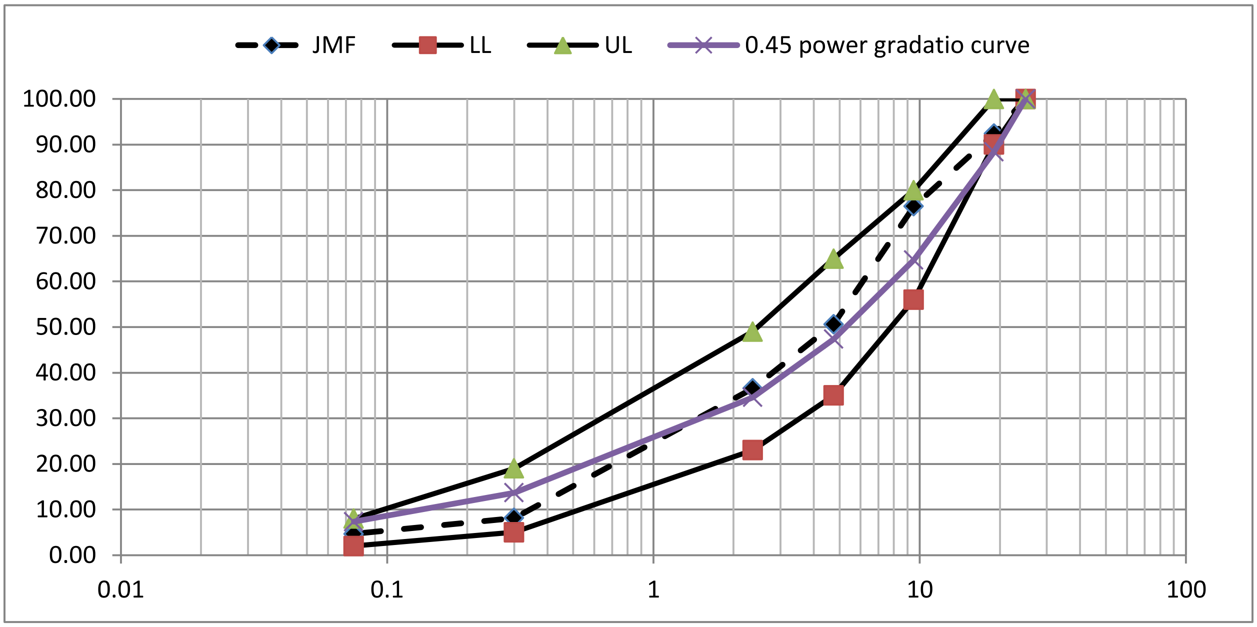

Fig. 4. 10 Gradation curve for natural aggregate

4.4.4. Bulk and Maximum Specific Gravity Tests

After preparation of specimens for five different bitumen contents by mixing and compaction, bulk specific gravities of each specimen were determined for different proportion of crushed concrete aggregate and natural aggregates and maximum specific gravities was determined at two bitumen contents and the remaining was calculated from the formula correlated with effective specific gravity of the aggregate. Table 4.12 presents maximum and table 4.13 presents bulk specific gravity results of the paving mixtures at different proportions.

Table 4. 12 Theoretical maximum specific gravity for different CCA proportion

Average Theoretical Maximum Specific Gravity (Gmm)										
Bitumen content (%)	**4.00**	**4.50**	**5.00**	**5.50**	**6.00**	**6.50**	**7.00**	**7.50**	**8.00**	**8.50**
0% CCA	2.63	2.60	2.57	2.56	2.52	-	-	-	-	-
30% CCA	-	-	-	2.52	2.50	2.48	2.46	2.44	-	-
50% CCA	-	-	-	-	-	2.40	2.38	2.36	2.35	2.33
100% CCA	-	-	-	-	-	2.28	2.21	2.14	2.08	2.04

Table 4. 13 Bulk Specific Gravity of paving mixtures at different proportions of CCA

Average Bulk Specific Gravity (Gmb)										
Bitumen content (%)	**4.00**	**4.50**	**5.00**	**5.50**	**6.00**	**6.50**	**7.00**	**7.50**	**8.00**	**8.50**
0% CCA	2.44	2.46	2.48	2.51	2.50	-	-	-	-	-
30% CCA	-	-	-	2.24	2.28	2.31	2.32	2.32	-	-
50% CCA	-	-	-	-	-	2.19	2.22	2.22	2.24	2.23
100% CCA	-	-	-	-	-	1.96	1.97	1.98	1.96	1.95

4.4.5. Volumetric analysis results

From the results of specific gravities presented above, volumetric analyses are done. The volumetric analysis includes the voids in total mix/ air void (Va), the voids in mineral aggregate (VMA), the voids filled with asphalt (VFA), effective bitumen content and absorbed bitumen. The results are shown in table 4.14 for different aggregate proportions of the mix.

Table 4. 14 Volumetric results for different proportions of CCA

Bitumen content		**4.00**	**4.50**	**5.00**	**5.50**	**6.00**	**6.50**	**7.00**	**7.50**	**8.00**	**8.50**
Effective bitumen content [Pbe](%)	**0%**	3.26	3.76	4.26	4.76	5.26					
	30%				3.83	4.33	4.83	5.33	5.83		
	50%						4.13	4.63	5.13	5.63	6.13
	100%						2.53	3.03	3.53	4.03	4.53
Air voids (Va) (%)	**0%**	7.16	5.16	3.38	2.00	1.03					
	30%				11.08	8.60	6.96	5.81	4.85		
	50%						8.81	6.56	5.91	4.63	4.44
	100%						13.93	10.64	7.12	5.81	4.13

Average VMA (%)	**0%**	14.70	14.30	14.10	13.80	14.50					
	30%				17.10	15.80	15.40	15.50	15.70		
	50%						15.00	14.00	14.50	14.40	15.30
	100%						14.00	13.30	13.40	14.70	15.70
Average VFA (%)	**0%**	51.30	63.90	76.00	85.50	92.90					
	30%				35.20	45.60	54.80	62.50	69.10		
	50%						41.30	53.10	59.20	67.80	71.00
	100%						0.50	20.00	46.90	60.50	73.70
Stability (KN)	**0%**	8.97	9.76	9.13	8.94	8.20					
	30%				11.56	12.77	12.65	12.26	12.42		
	50%						13.23	13.32	12.54	11.03	10.86
	100%						11.56	10.53	9.88	9.50	10.17
Flow (mm)	**0%**	2.97	3.20	3.37	3.60	4.10					
	30%				3.23	3.46	3.67	3.49	3.87		
	50%						3.27	3.39	4.55	4.44	6.01
	100%						3.27	3.66	3.78	3.89	4.27

Using these results and the results from stability and flow test graphical plots were drawn in spreadsheet which will best fit. The plots for each proportions of aggregate mix and for each properties analyzed and tested are presented through fig 4.11-4.16.

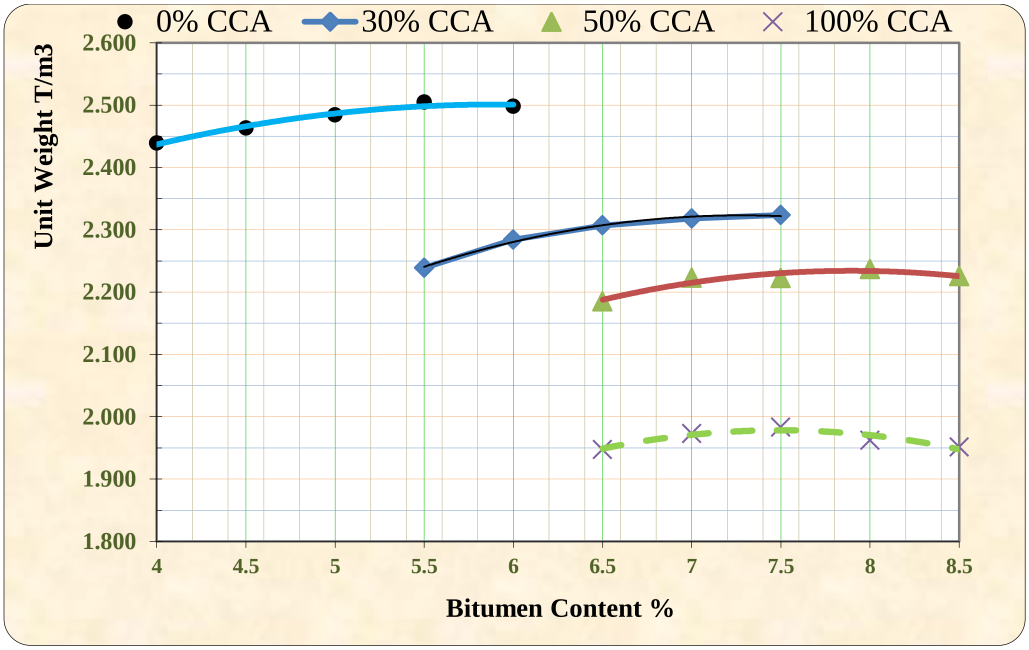

Fig. 4. 11 Unit Weight vs. Bitumen quantity

Unit weight curves: The unit weight of the paving mixture decreases when the percentage of crushed concrete aggregate increases. This is due to the presence of mortar in CCA. The mortar in CCA has light weight since it is not belong to basaltic or other types of natural aggregate. There is no specification for maximum or minimum value of unit weight but when the aggregate has light weight special considerations will be taken in designing it (Bob M. Gallaway, 1980). Being light weight has substantial effect in other characteristics of the paving mixture.

The density increases with increase of bitumen content to a certain extent and start to decrease after peak point. This is due to that the absorbed bitumen filled the voids in mineral aggregate and the remaining bitumen takes the place of the air voids between inter granular space until the peak demand of bitumen. When the bitumen increases, the excess bitumen beyond inter granular voids takes the space of the aggregate and the aggregate is replaced by bitumen which had lower density than aggregate. This leads to the decrease of unit weight in paving mixture.

Voids in Total Mix (VTM): the air void decreases as bitumen content increases. The air voids increases when the proportion of CCA aggregate increases. This trend of air void is also reported by the researches of (Paranavithana & Mohajerani, 2003; a. R. R. Pasandín & Pérez, 2013; A. R. Pasandín & Pérez, 2014; Pérez et al., 2012). The attribute for this trend of air void will be due to the absorptive properties of the porous portion which will create thicker film thickness which in turn hinders the interlocking of aggregates. In addition to this at a time of compaction, the attached mortar will be detached from the natural aggregate which will in turn add the fishers from the crushed mortar. This detached mortar also will not absorb bitumen and left un-compacted in the mix since there is no binding bitumen.

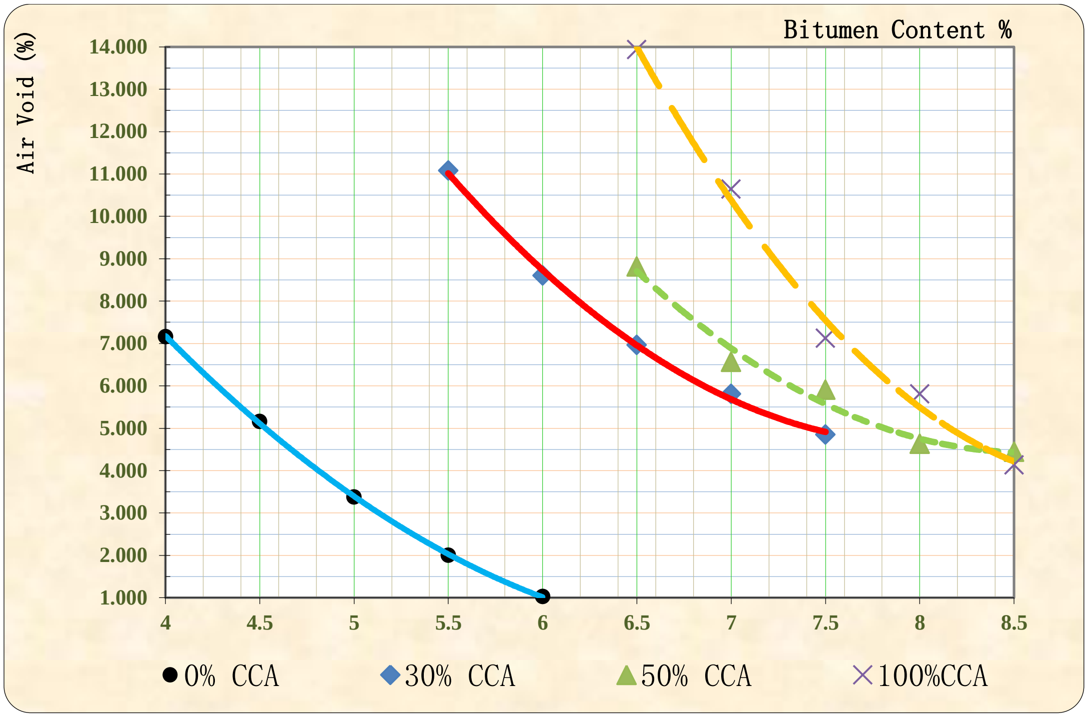

Fig. 4. 12 Air Void vs. Bitumen quantity

Void in mineral aggregate (VMA): VMA is the total volume of voids within the mass of the compacted aggregate. Initially the VMA decreases as bitumen content increases since the voids are filled with bitumen and reach to some minimum infliction point and start to increase. The cause for increment of VMA when the bitumen increases in excess of absorbed bitumen and the effective bitumen which fills inter granular voids between the particles is the thick film thickness. This film thickness hinders the aggregate to bind each other and this will increase the voids in mineral aggregate. The same result is found as some literatures indicate(Bhusal & Wen, 2013; Mills-Beale & You, 2010) as the content of RCA increases the VMA and VFA decreases. VMA in natural aggregate mix shows consistent variation and less than VMA in crushed concrete aggregate mixes at lower content of RCA. In crushed concrete aggregate the VMA is higher at 30% CCA and the other 50% & 100% has lower minimum value and also higher variation in constant bitumen content. The void space due to porosity of the RCA will be the possible cause to increases the VMA. The angularity of CCA will lead to the lesser VMA when CCA increases. Inter granular matrix between the natural aggregate and crushed concrete aggregate will had significant effect on volumetric properties of the paving mixture.

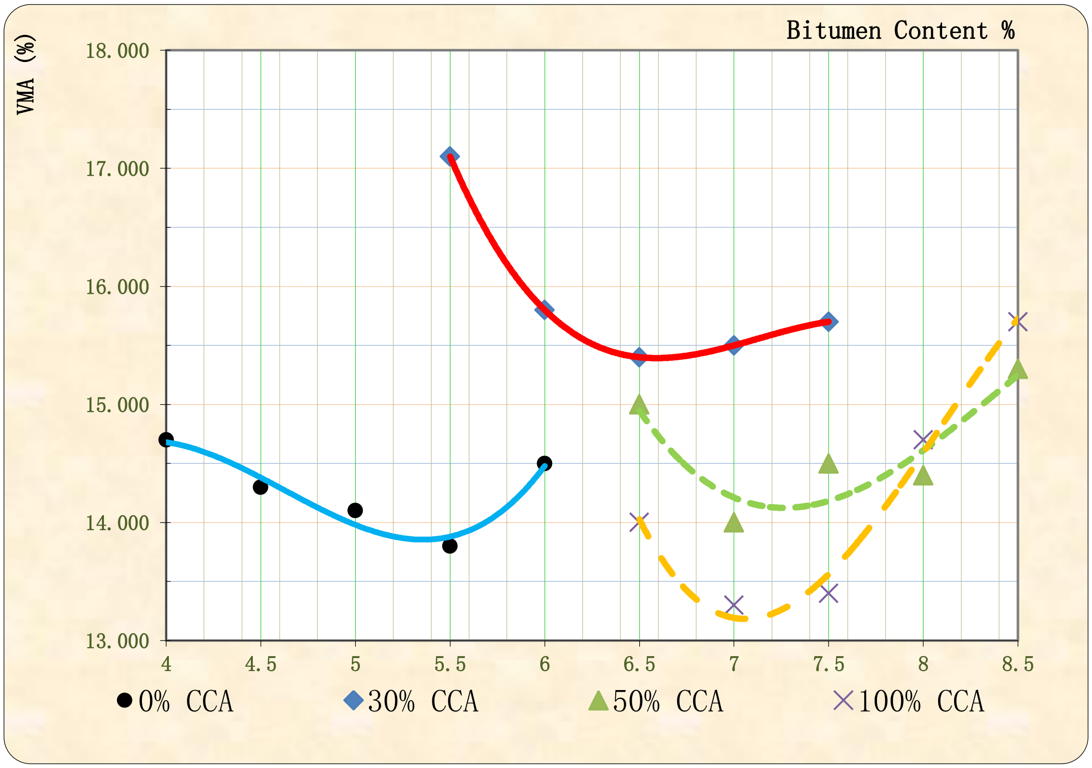

Fig. 4. 13 Void in Mineral Aggregate (VMA) vs. Bitumen Content

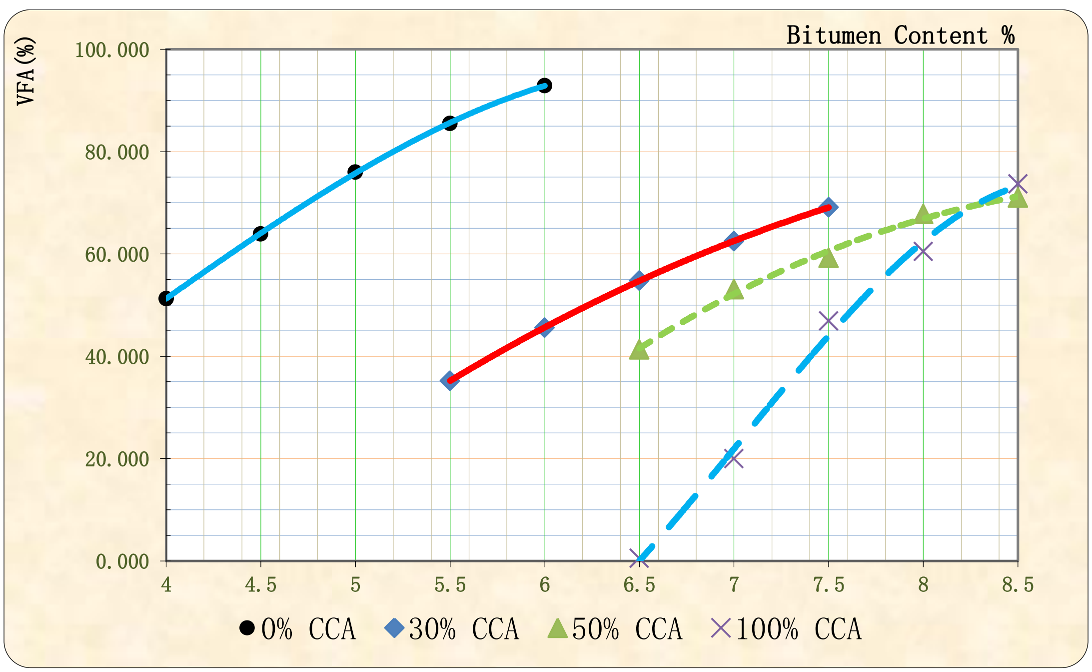

Fig. 4. 14 Voids Filled with Asphalt (VFA) vs. Bitumen Content

Voids Filled with Asphalt (VFA): VFA is the void in mineral aggregate excluding air void. This value increases linearly with bitumen content. The VFA deceased when the percentage of CCA increases in the mix this is also mentioned by (Bhusal & Wen, 2013; Mills-Beale & You, 2010). This is due to the absorption value of CCA increment and thicker film thickness with CCA amount.

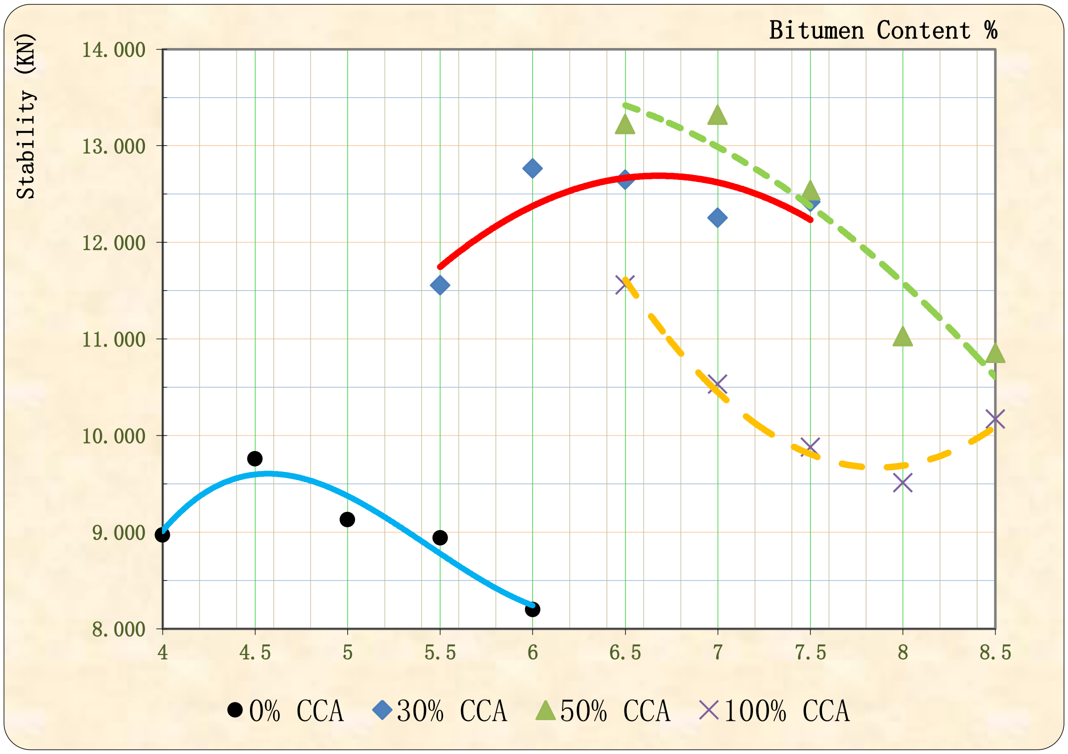

Fig. 4. 15 Stability vs. Bitumen Content

Stability: stability is the ability of the bituminous mixture to resist excessive permanent deformations. The normal trend of stability in Marshall Mix increases with increasing asphalt content, reaches a peak and then decreases. The trend for 50% CCA shows decreasing of stability as bitumen content increases and does not show peak point. This curve is common for some recycled aggregate HMA as mentioned by (Roberts L. F. et al, 1996). The stability of natural aggregate mixture is less than CCA incorporated mixes as also investigated by (Pérez et al., 2012; Wong, Sun & Lai D., 2007) even if the other literatures obtained opposite result and the other obtained similar stability value with natural aggregate asphalt. Stability increases as the percentage of CCA increases in the mixture. But at 100% CCA the stability shows lower value than 50% & 30% CCA. The curve of stability at 100% CCA shows opposite trend of the natural aggregate. Curing of the mix for 3hrs were tested at 6.4% bitumen content and 100% CCA for the difference in stability. The result shows that stability increases when curing for 3hrs. Stability for cured mixture is **12.87KN**, and for normal mix **10.53KN.** But on the contrary, void in a mix increases. The possible cause for increment of stability will be the air void in the mix, which will allow to deform before rupturing. The angularity of crushed concrete aggregate will also had substantial effect on the stability property.

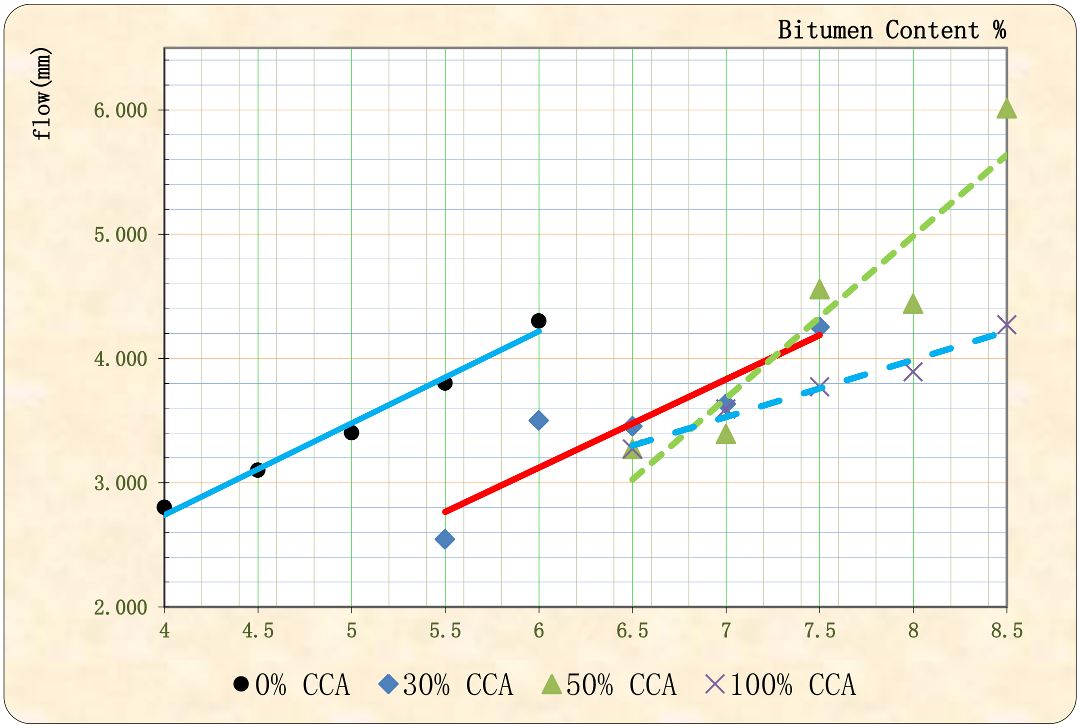

Fig. 4. 16 Flow vs. Bitumen Content

Flow: flow increases when asphalt content increases. High flow indicates plastic mix which will be prone to permanent deformation. While low flow indicates brittle mix. The flow value increases while incorporation of crushed concrete aggregate increases. This is due to the increase in bitumen for CCA incorporated aggregate. Flow at 50% CCA increases highly compared to 100% CCA with the same bitumen content. This is due to the absorptive property of CCA. At 100% CCA absorption of bitumen is higher than 50% CCA. Hence the unabsorbed bitumen is the cause to greater flow.

4.5. Design Bitumen Content Determination

From the charts above the design bitumen contents are determined for each type of paving mixture. The design bitumen content is determined in two methods: Asphalt Institute method (MS-2) and NAPA method.

In NAPA method the asphalt content is determined at the mid specification of air voids (in most specifications 4%), here ERA specifies for heavy traffic 5% air voids. Hence at 5% air void bitumen contents are taken and the other criteria are checked. When recycled concrete aggregate increases in the mix the optimum bitumen content increases. The VMA, VFA & stability criteria in accordance to ERA specifications are met for every paving mixture in analysis. But flow is out of the specification limit for 50% & 100% CCA. The result of bitumen content at 5% air void is shown in Fig 4.17 below.

The second method, asphalt institute method is determining the bitumen content at maximum stability, determining the bitumen content at maximum density and the bitumen content at 5% air void and these three values were averaged. Even if the bitumen content in this method is lower than the first one the VFA & air void in CCA incorporated mix does not satisfied the specifications.

Table 4. 15 Summary of Marshall mix test results & corresponding specifications.

	RCA %				**Specification (ERA)**	**Remark**
	0	30	50	100		
Design Bitumen Content (%)	4.6	7.4	7.8	8.4	**–**	
Air Voids (%)	5	5	5	5	**3-5**	
VMA (%)	14.15	16.1	14.9	14	**Min 14.0**	
VFA (%)	66.8	68	66	71.7	**65-75**	
Density (g/cc)	2.47	2.32	2.23	1.85	**–**	
Stability (KN)	9.45	12.63	11.9	10.1	**Min 9.0**	
Flow (mm)	3.4	4	4.5	4.75	**2-4**	Out of Spec at 50 & 100% CCA

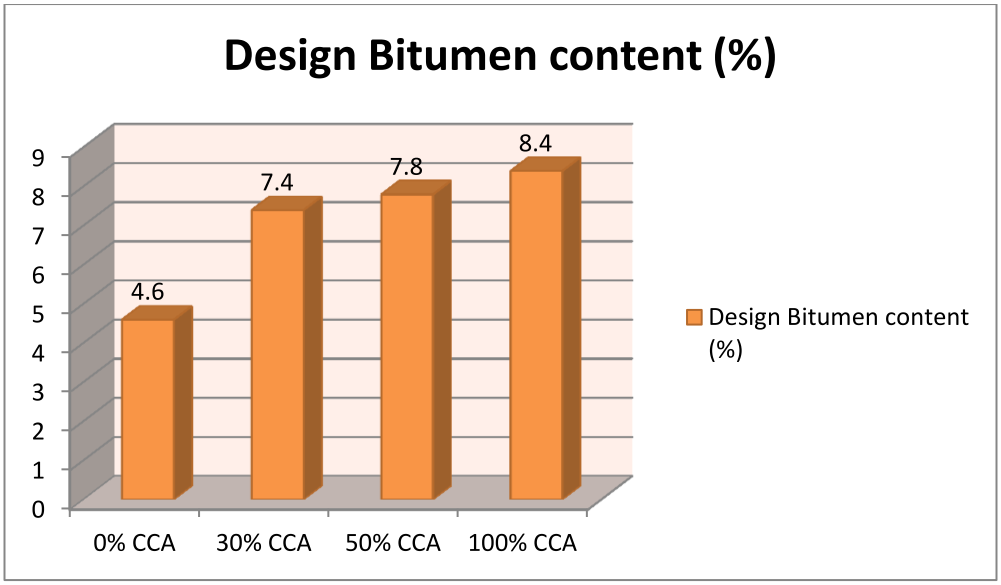

Fig. 4. 17 Bitumen content at 5% air void

4.6. Indirect Tensile Strength (ITS) Test

This test was conducted to assess the moisture induced damage of the compacted paving mixture. The test was conducted since the absorption of CCA is higher and the design air void was at maximum limit. This test could characterize the chemical property of bitumen affinity of aggregate. The stripping problem is suspected in crushed concrete aggregate due to water loving characteristics of the porous mortar in CCA. Hence moisture induced damage characterizes this stripping problem of the paving mixture. This test is conducted for 30% & 50% CCA only since for natural aggregate moisture induced damage is not susceptible and 100% CCA is not investigated since the absorption property hinders to use 100% CCA in HMA from quality test. The tests results are shown in table 4.19 & 4.20.

Table 4. 16 ITS result for 30% CCA

ITS test Result	Dry Subsets		Wet Subsets	
	A	B	C	D
Load (P),N	1082.60	9745.00	9251.00	9302.00
Strength (S), Mpa	925.18	1006.90	909.99	925.17
Average	966.05		917.58	
Tensile Strength Ratio (Wet/Dry),%	94.98			

Table 4. 17 ITS result for 50% CCA

ITS test Result	Dry Subsets		Wet Subsets	
	A	B	C	D
Load (P),N	9212.00	9116.00	7856.00	7913.00
Strength (S), Mpa	899.09	893.90	772.77	780.83
Average	896.50		776.80	
Tensile Strength Ratio (Wet/Dry),%	86.65			

The volumetric, stability and flow values for the different composition of the aggregate revealed that incorporating crushed concrete aggregate up to 30% fulfill every marshal mix criteria whereas at 50% and 100% CCA the flow value is beyond the specification. Accommodation of this value to some extent will be possible based on the project specific attributes. The grade of bitumen will also influence this characteristic. The other observation is the bitumen content. The bitumen content increases when the portion of crushed concrete aggregate increases. The indirect tensile strength result shows better value for lower crushed concrete aggregate incorporation. Both at 30% CCA and 50% CCA the indirect tensile strength ratio exceeds the specification limit which is >**79%** without any treatment. Even though this is the fact to moisture induced damage due to absorptive properties of recycled aggregate some measures could be taken to incorporate the recycled aggregate. Among those curing of the mixtures in oven for some hours is one of the methods investigated by (A. R. Pasandín & Pérez, 2014).

4.7. Economics of utilizing crushed concrete aggregate

It is obvious that recycling of concrete as aggregate will give astonishing environmental advantage with the side of preserving natural aggregate and preserving landfills which is the main issues for waste disposal especially in the capital of the country. In addition to this environmental conservation the monetary virtues of recycling concrete aggregate will depend on different subjective and objective factors. To encourage the utilization of recycled concrete aggregate some direct saving will be considered by individuals. To choose construction and demolition derived aggregate whenever:

$$Qp + Tq > Er + RCp + Tr - - - - - - - - (4.4)$$

Where:

Qp= price of newly quarried product at quarry gate

Tq= transport cost from quarry to site

Er= any extra costs created by using CDW derived aggregate

Rcp= price of recycled product at recycling gate

Tr= cost of transportation from recycling center to site (Symonds, in association with ARGUS, 1999)

Price of newly quarried aggregate will be assumed fixed by market forces. The supply and demand maintain the price of this naturally quarried aggregate. The transportation cost depends on the site location where the quarry or the crushing unit is found. The transportation cost for the quarried product will not be significantly different from transportation of recycled aggregate unless the recycling unit there in- situ. The quarrying will require more emission and energy consumption than transporting the demolition and construction wastes. Er is made up of an 'objective component' and a 'subjective component', representing the price advantage which the user demands before buying C&DW-derived aggregates instead of primary material. The objective component may be quite small, but is likely to include additional storage and cleaning costs at the location where the aggregates are to be used, as a result of needing to maintain separate stockpiles and to switch machines over between batches. C&DW-derived aggregates sometimes also need to be wetted before mixing, unlike primary aggregates. The rest of Er represents the 'subjective component', which is the value which the user places on the intangible benefits of using primary materials.

In this research some raw data were collected to analyze the cost of recycling against disposing off construction demolitions and recycling against utilizing natural crushed aggregates. The analysis result is presented below in table 4.18 & 4.19.

Table 4. 18 Cost analysis of recycling of CDW and utilizing primary aggregate

	I) Cost of crushed concrete aggregate to recycling	total cost/m^3 (birr)	Remark
1	Demolition & sorting cost	20.75	cosidered for demolition into portable size & metal separation
2	Transportation cost to recycling plant	6.67	considered for 1 km
3	Crushing Cost	46.67	
4	Stockpiling & wetting cost	2.67	
5	Transportation cost to final destiny	6.67	considered for 1 km
	Total cost of CCA (birr)	**83.42**	
	II) Benefits gained due to Recycling against Disposal		Remark
1	landfill saving (disposing cost)		
2	transportation to landfill cost		considered for 1 km
3	Saving from recovered metal		for reinforced concrete only
	Total saving of recyclying against disposing		
	III) Costs of Natural aggregate from Quarry	total cost/m^3 (birr)	Remark
1	Quarrying cost	40	considering for simple quarriying system which does not require blasting and other advanced mechanisms
2	Transportation cost of quarried rock	6.67	considered for 1 km
3	Crushing cost	33.33	
4	Selling price	289.55	variable for variable quality
5	Transportation cost to final destiny	6.67	
	Total cost of naturally quarried aggregate	**376.22**	

The economics of recycling versus disposal

Disposal will sometimes cost more than recycling when there is no enough or nearby landfill areas. Hence the decision will depend on the owner in demand of demolition. The decision between recycling and disposal will depend on the following attributes.

$$Vm(Tm + Dm) > V1(T1 + R/D1 - Sv1) + V2(T2 + R/D2 - Sv2) + \ldots\ldots$$

$$\ldots\ldots + Vn(Tn + R/Dn - Svn) + Es$$

Where:

Vm- volume of unsorted CDW,

Tm- Cost of transporting unsorted waste to disposal waste to disposal site

Dm- cost of disposing of unsorted waste,

V1- volume of inert waste,

R/D1- cost of recycling or disposing of inert waste (including quality control costs

SV1- sale value of recycled product (if relevant)

2…..n- other sorted waste streams

Es = Additional costs of separate demolition and materials sorting

However the decision of utilizing crushed concrete aggregate by recycling or completely disposing depends on the volume of the CDW, the distance of the demolishing site to the recycling unit, the cost of landfill, additional costs of treatment for demolition materials like sorting and the subjective decisions.

For the future consent of utilization of CCA this model can be easily applied and used by anyone who considers it.

If the aggregate obtained from crushed concrete aggregate gives better cost than the natural aggregate in addition to environmental advantages, it would reimburse the cost for extra bitumen. The cost of extra bitumen required due incorporation RCA shall be evaluated with the saving gained from utilizing RCA.

Hence utilizing crushed concrete aggregate in construction of road pavement rather than disposing off it and utilizing primary virgin aggregate had a financial saving of **387.86** birr/m^3.

This saving seems very attractive if the volume of concrete in construction and demolition waste is plenty enough.

In addition to this financial saving environmental protection should be given great concern.

Table 4. 19 Summary of cost analysis of CCA vs. Virgin aggregate

Total cost of Recycling CCA (birr)/m3	**83.42**
Total saving of recycling against disposing(birr)/m3	**95.17**
Total cost of naturally quarried aggregate	**376.22**
Net Saving of recycling against disposal (birr)/m3	**11.75**
Net saving of recycling against virgin aggregate utilization(birr)/m3	**387.96**

CHAPTER 5- Conclusions & Recommendations

5.1. CONCLUSIONS

In this research, laboratory tests were conducted to evaluate the physical and geotechnical properties of crushed concrete aggregate collected from demolished site of Addis Ababa University compound and crushed to appropriate size with aggregate crusher. Different tests were conducted and the results are evaluated with corresponding ERA specifications of unbounded base course. This research also investigated volumetric properties of hot mix asphalt prepared by Marshall Mix design method where the constituents were crushed concrete aggregate and natural crushed aggregate. Based on the mix design optimum asphalt content was determined for four different percentage composition of natural and crushed concrete aggregate. Additionally moisture induced damage was evaluated in laboratory for different compositions of crushed concrete and natural aggregate at the respective optimum bitumen content. This section summarizes the overall findings achieved through the research to achieve the objectives of the research as follows:

One of the objectives was to evaluate the physical and geotechnical properties of crushed concrete aggregate and compare the properties with natural crushed aggregate and evaluate in terms of ERA specification for unbounded base courses. Accordingly the test results revealed that recycled concrete has lower specific gravity and higher absorption which is emanated from porous attached mortar to the innate aggregate. These attributes significantly affect the strength and durability characteristics of crushed concrete aggregates which makes less durable, less strong and more moisture susceptible than natural aggregates. Even though ten percent fines value has marginal value other durability and strength measuring parameters like LAA, ACV and CBR shows better value which are in the limit of ERA specification for unbounded base course. Hence crushed concrete aggregate can be utilized as Granular Base 2(GB 2) and Granular Base 3 (GB 3) without any treatment.

The other objective was to determine the optimum bitumen content for different proportions of RCA replacement to natural aggregate. through the process of optimum bitumen content determination, the volumetric properties of the paving mixture prepared by Marshall Mix design method was assessed and observed that the air voids in crushed concrete aggregate is higher and above expected (4%) even at higher bitumen content. The cause for this will be the breaking of the attached mortar through Marshall Compaction of 75*2 blows which will create uncoated surface and more void in the mix. It was investigated if the cause for this higher void will stem from the calculation of the maximum theoretical density. But the maximum theoretical density determination from laboratory prepared loose specimen has no significant difference from maximum theoretical density determined from compacted specimen. Optimum bitumen content increases when the percentage of recycled concrete aggregate increases. The bitumen content ranges from 7.4%- 8.4% by weight when the Crushed concrete aggregate percentage increases from 30%- 100% whereas the optimum bitumen content for natural aggregate is 4.6%. The possible cause for this attribute will be the absorptive property of the mortar in recycled concrete aggregate. 100% & 50% crushed concrete aggregate does not fulfill the ERA and MS-2 criteria of flow range from 2-4. This will be the limitation to replace natural aggregate to these proportions unless other considerations are taken to accommodate to a certain deviation value for specific projects.

The stability of hot mix asphalt with crushed concrete aggregate increases as the percentage of incorporated crushed concrete aggregate increases but at 100% CCA the case does not applied. The stability of mixture with natural aggregate is less than the stability of the paving mix with CCA.

The remaining objective was to assess moisture induced damage of paving mixture incorporating crushed concrete aggregate in laboratory. The test result revealed that moisture induced damage increases as the percentage of crushed concrete aggregate increases. the ITS test conducted to assess moisture susceptibility of paving mixture revealed that the tensile strength ratio of conditioned specimen to dry specimens gives satisfactory result when evaluated according to ERA specification up to 50% replacement of natural aggregate with crushed concrete aggregate.

Even though it is possible to replace course and fine crushed concrete aggregate for natural aggregate in surface wearing course up to 30% for heavy traffic (> 5 millon ESA), the higher bitumen consumption hinders to replace the natural aggregate to any level for the country like Ethiopia. The main reason for this deduction is that of the economic advantage. Since bitumen is imported with foreign currency and aggregates are found in abundance in the country, utilizing crushed concrete aggregate in hot mix asphalt will have economic disadvantage in pavement construction. Therefore further researches and treatments are required to replace crushed concrete aggregate to some extent of natural aggregate in hot mix asphalt.

5.2. RECOMMENDATIONS

This research was carried out using particular crushed concrete aggregate and hence, extensive field and laboratory experimental results should be addressed in considering practical applications of a wider range of these recycled materials. Since the performance and the properties of recycled aggregate hot mix asphalt is largely depending on the nature of virgin aggregate, the nature and origin of recycled concrete aggregate, the treatment used to improve the recycled concrete aggregate properties and the type of mineral filler used immense works are remaining regarding to recycling of aggregates for road construction purpose.

Recycled aggregate can be considered for other types of applications like as sub base, fill under pipe beddings, for construction of new concrete, backfilling around structures, as filler material in hot mix asphalt and for others with extensive researches and giving concern by the respective authorities for recycling of construction and demolition wastes to preserve the natural resources and to preserve landfills.

Recycling of construction and demolition wastes shall not be considered only from point of view of direct monetary savings, but also from environmental protection, landfill conservation, energy savings and other mutual savings. Life cycle cost analysis can be conducted for the entire feasibility of recycling of construction and demolition wastes.

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Appendix: Laboratory Test Results

Appendix A: Physical & Geotechnical Test Results

Appendix B: Bitumen Quality Test Results

Appendix C: HMA Test Results

Appendix D: Indirect Tensile Strength Test Results

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