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Assessment of the Recycled Concrete Aggregates Structural Suitability for Road Construction

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To My Parents

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Abstract

In most aspects of modern life, there is a consensus among practitioners and decision makers of the importance of preserving the environment, and to find alternatives to the scarce natural materials. This can be accomplished by better utilization of the natural materials and/or recycling or reclaiming their waste, specially, if they are of finite resources. The recycled material could be an attractive alternative (both environmentally and economically) if its characteristics are proven to be close to those of the natural material.

Utilizing recycled mineral aggregates in the construction field in general and in highway pavement in specific is somehow governed by its ability to meet its intended function as carrying component within the structure. In the area of pavement construction, the suitability of the recycled aggregates is primarily judged by its ability to carry the high traffic loads effectively.

The primary objective of this thesis is to study the suitability of using the Recycled Concrete Aggregates (RCA) for pavement construction or rehabilitation. The RCA is intended to replace the virgin material in one of the pavement layers, namely the subabse. The general characteristics of the RCA material (such as the grade distribution) are compared against the subbase material specifications. A testing model is built to quantify the RCA-layered pavement performance under various load

levels, and to comparatively assess its behavior against the virgin mineral aggregates. The model dimensions are set large enough to replicate the pavement structures in reality to ensure accurate analysis.

Several experimental settings are considered to account for the possible variability in the pavement loads (generated by the various vehicle types), material gradation, composition and thickness. The performance of the RCA material is captured through the resulting load-deflection relationships of the various settings.

The results of these experiments indicated the good potential of the RCA as a subbase material. The resulting load-deflection relationships of both the RCA- and virgin-materials indicated the superiority of the RCA-material as a subbase material. In general the deflection results of the experiments indicated that the pavement deflection under load is generally lesser with the RCA material.

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Abbreviation

RCA	Recycled Concrete Aggregate
UAE	United Arab Emirates
WD	Works Department
BCSJ	Building Contactors Society of Japan
RAC	Recycled Aggregate Concrete
PCC	Portland Cement Concrete
MSW	Municipal Solid Waste
MWC	Municipal Waste Combustors
TRB	Transportation Research Board
PCCP	Portland Cement Concrete Pavement
RCP	Recycled Concrete Pavement
CTB	Cement Treated Base
HMA	Hot Mix Asphalt
KDOT	Kansas Department of Transportation
AC	Asphalt Concrete
RA	Recycled Aggregate
NA	Natural Aggregate
BBRI	Belgian Building Research Institute
DM	Dubai Municipality
CBR	California Bearing Ratio
LA	Los Angeles

CHAPTER ONE

Chapter One

Introduction

1.1 The Problem

In most aspects of modern life, there is a consensus among practitioners and decision makers of the importance of preserving the environment, and to find alternatives to the scarce natural materials. This can be accomplished by better utilization of the natural materials and/or recycling or reclaiming their waste, specially, if they are of finite resources. The recycled material could be an attractive alternative (both environmentally and economically) if its characteristics are proven to be close to those of the natural material. Recycling is the process of re-establishing the previously discarded material, given that the properties of the refurnished material are suitable for the purpose they are to be re-established for. Recycled Concrete Aggregates (RCA) are defined as "the aggregates produced by the crushing of original concrete; such aggregates can be fine recycled aggregates or coarse recycled aggregates" [1]. Barring in mind the tremendous amounts of concrete waste produced, and the environmental problems that they develop, not to mention the cost of discarding it appropriately, it may be sensible to reuse them by recycling. Better understanding of the behavior of RCA is thus essential; particularly if these materials are to be considered as a suitable alternative to the aggregates in concrete or road construction.

Demolishing old concrete structures and replacing them by new and modern ones is becoming a common feature in the cities evolving through rapid urbanization. The United Arab Emirates in particular has rapidly experienced urbanization that has involved reconstruction in several fields such as high-rise buildings, highways, bridges, airports, and seaports. This development results in the production of massive amounts of concrete material.

The main component of building construction materials is aggregates. The majority of those used in construction are natural processed aggregates, obtained primarily from mountains and hard land surfaces. The extraction and processing of the aggregates greatly contribute to the environmental imbalance through the production of huge amount of dust, which affect humans, plants and the wildlife.

1.2 Objectives of the Thesis

The main objective of this thesis is to investigate the suitability and potential benefits of using the waste concrete materials in the area of highways construction. To fulfill this objective, the following items are considered:

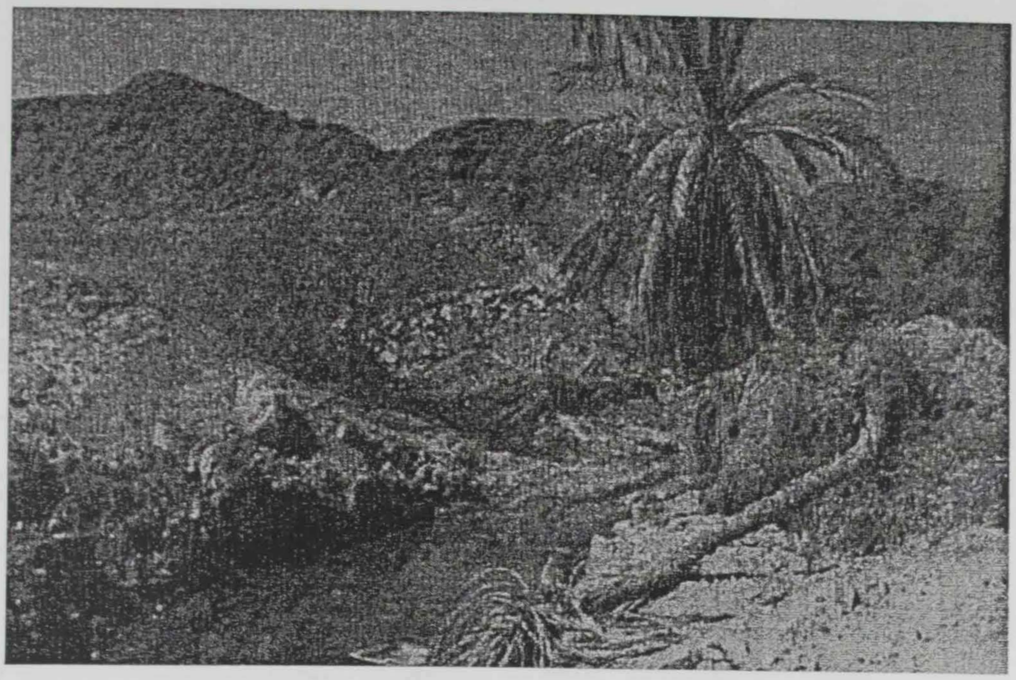
- This work is intended to study the behavior of the RCA as subbase material in pavement construction and to conduct comparative analysis of the behavior of the recycled concrete material against the natural virgin material. The behavior will be evaluated mainly by studying the performance of the material under various loading intensities. The outcome of the performance study of the RCA will be utilized to assess the suitability of the RCA when incorporated within the pavement structure.
- The modeling framework and experiments should enable us to quantify the real life performance of the material. That is, it should permit replication of the actual behavior under loading.
- Furthermore, this work is intended to study specifically the effect of the RCA layer depth and size grading within the pavement body on the performance of the pavement under loads.

1.3 Environmental Impact of Aggregate Crushing

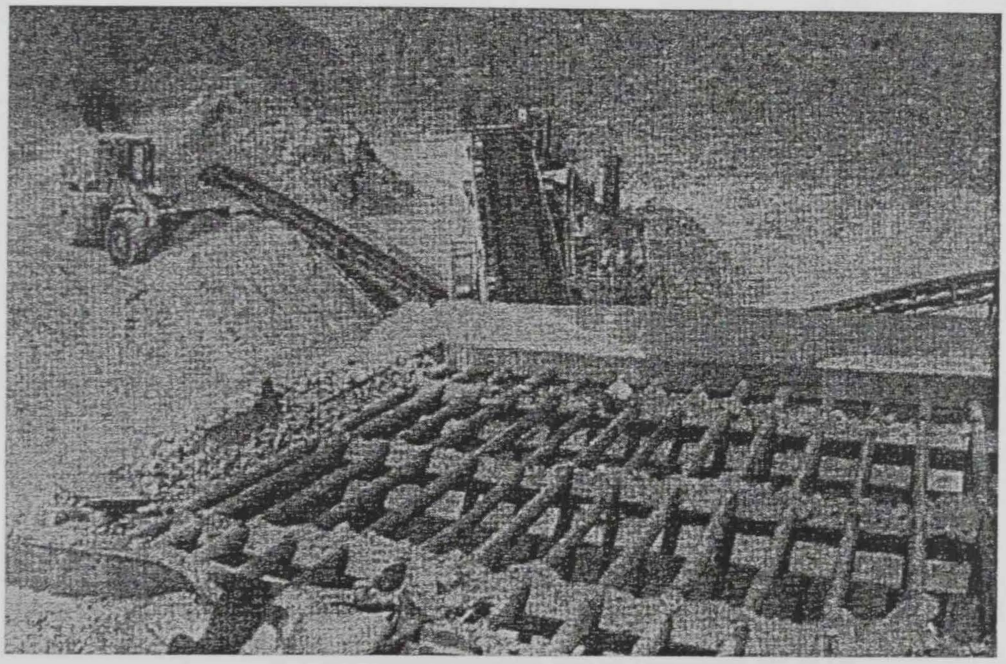
Waste materials occupy large disposal areas and result in serious detrimental effects to the environment. Every year, there are thousands of tons of demolished concrete produced in the world. These waste products are dumped in large holes, such as old quarries. Over time, the dumped materials cause serious surface and underground pollution. The infiltration of the fine particles (especially in rainy areas) causes contamination of the underground water and leads to major adverse impacts on all livings utilizing such water. Figure 1.1 shows a concrete disposal area in Al Ain city, UAE.

Figure (1.1): A Disposal Area in Al Ain City, U.A.E.

The main component of road and building construction is aggregates, which are basically obtained from crushing mountain rocks and hard lands. In UAE, aggregates production is conceived to be one of the most serious adverse impacts on environment and humans. People in Mezaireea often complain about the quarries near the area where they live (see Figure 1.2). Similar situations are observed all over the country. The Mezaireea area is exposed to high levels of pollution caused by the quarries operating 24 hours a day; a cloud of dust covers the area. The children in the area are breathe in the quarries' dust, and have started to suffer from several diseases such as asthma, allergies, and chest infections.



(a)



(b)

Figure (1.2): The Mezaireea Quarries Area: (a) Dead Trees (b) Some of the Quarry Equipment

In general, concrete accounts for more than 75% by weight of all construction materials in the UAE. Statistics from Dubai Municipality indicate an increase in building waste material [2]. Figure 1.3 shows the amount of building waste in the Emirate of Dubai from 1993 to 1999. There are more than 2.5 million tons per year of these products in the Emirate of Dubai only [2]. The annual reports of the Waste Management Section in Dubai Municipality are incorporated in Appendix A for reference.

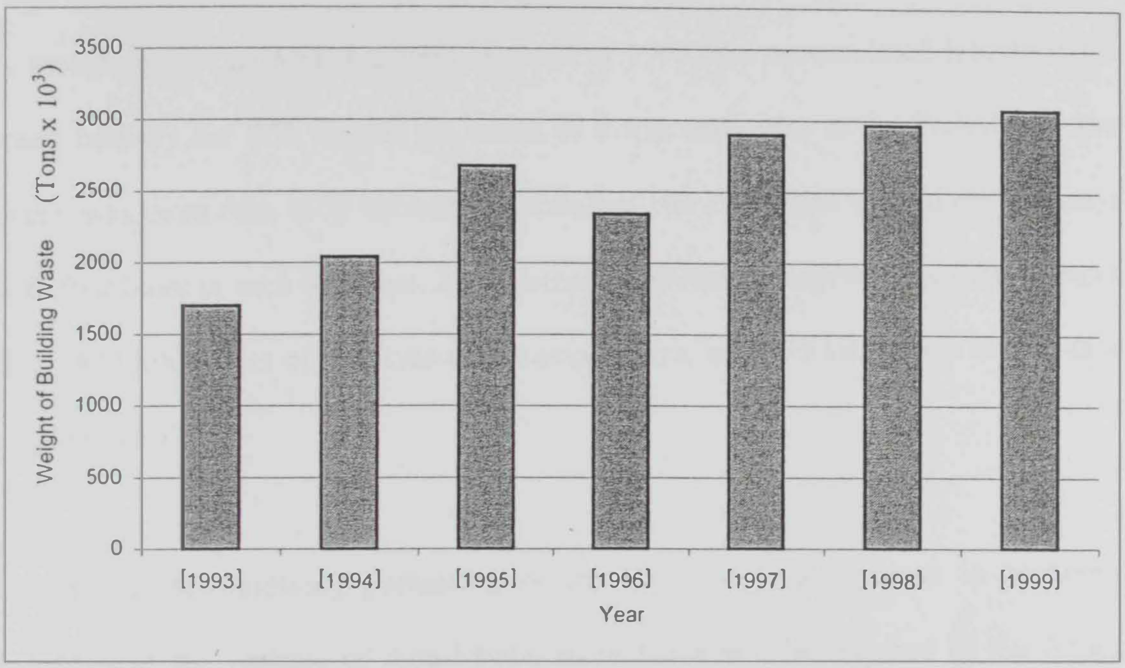


Figure (1.3): Building Waste Amounts in the Emirate of Dubai (1993 – 1999)

1.4 Roads in UAE (Example of Emirate of Abu Dhabi)

Building roads, bridges and intersections in the Emirate of Abu Dhabi is the sole responsibility of the Works Department (WD), which has since its establishment spent a staggering Dhs. 20 billion building approximately 9000 kilometers of roads, including internal roads inside the various towns and cities in the Emirate, inter-city roads within the Emirate, and outer roads linking Abu Dhabi to the other emirates.

The Roads Section in the WD's Transportation and Services Directorate sets out building roads whenever it receives instructions for this from the higher authorities, or whenever the need arises for roads due to other constructions. For example, if a cluster of houses is being built in a certain area, service roads will be required. The Roads Section proposes the establishment of these roads after coordinating with the other concerned departments.

A recent survey showed that until the end of 1996, the accumulated length of the roads built by the WD outside the limits of towns and cities in the Emirate of Abu Dhabi was more than 1300 kilometers, including 102 kilometers of dual carriageways with four lanes in each direction, 220 kilometers of dual carriageways with three lanes each, 470 kilometers of two lane dual carriageways, and 579 kilometers of two-lane single roads [3].

Due to the fast growing population of the UAE, and the increase in economic activities in the Emirate of Abu Dhabi, more roads will be required in the future, either to connect newly populated areas with existing areas or simply to replace roads that have become too small or too old to meet the needs of the day. There are many road projects in the design stage in the Emirate of Abu Dhabi, and the opportunity of using the RCA as a pavement layer in highway construction will always be a valid and economical choice if proven to have the required sustainability features of the virgin aggregates.

1.5 Thesis Outline

The aim of this thesis is to investigate the suitability of using waste concrete in the area of highway construction. This thesis is divided into five chapters. Chapter 1 covers the introduction; which mainly illustrates the problem and the objective of this thesis. The remainder of the thesis is organized as follows:

Chapter 2 reviews the relevant literature on the recycling of waste disposal and material recovery in general, and the use of such materials in highway construction in particular. It also introduces several studies in the area of concrete waste, recycling concrete, the current practice and the properties of recycled aggregate concrete. Case studies of concrete recycling are also presented.

Chapter 3 discusses the experimental methodology adopted in this study. A testing model is built to test and compare the RCA as a subbase material with the virgin material used in highway construction. The model (Mold) dimensions are set large enough to replicate the pavement structures in reality to ensure accurate analysis. The material used in testing and the method of measuring and compaction are also discussed in this chapter. Chapter 4 presents the results obtained from the different experiments. In addition, this chapter describes the analysis of the various models outcome and discusses the results in light of the deflection relationships obtained for each model. Chapter 5 addresses some of the general conclusions with suggestions for future research.

CHAPTER TWO

Chapter Two

Literature Review

2.1 Introduction

The environment has become an important issue all over the world. Concern for the environment increased and included social, political and economical matters. However, no matter how strong the social concern about the environment may be, and ignoring the technical possibilities, the recycling of concrete waste will always be an economic issue. Generally, the economic interest in recycled concrete materials is governed by the availability of such waste material, the cost of the natural material, the charges for dumping the waste material in the disposal spaces, and finally saving the transportation costs since the disposal spaces are usually at the far side of the city.

This chapter reviews existing studies on recycled concrete aggregates and other general related topics. Some important terms relating to recycled concrete are given, pavement standards used in the Emirate of Abu Dhabi are discussed. The chapter discusses also some general waste material, and waste materials used in highway construction. Waste concrete, the current practice of RCA, and Portland cement concrete pavement applications have been reviewed in this chapter. One of the important issues that discussed in this part is the properties of recycled concrete. Regional effects on recycling debris, damaging disasters and its effects have been studied also. The end of this chapter reviews the results of a comparison study in Dubai between recycled concrete aggregates and virgin aggregates.

2.2 Terminology

Partially based on a Japanese Proposed Standard on 'Recycled Aggregate and Recycled Aggregate Concrete' which was prepared by the Building Contractors Society of Japan in 1977, B.C.S.J., the following terminology is suggested, as given by Hansen in his book [1]:

2.2.1 Waste Concrete

Waste concrete is concrete debris from demolished structures as well as fresh and hardened concrete which have been rejected by ready-mixed or site-mixed concrete producers or by concrete product manufacturers.

2.2.2 Conventional Concrete

Concrete produced with natural sand as fine aggregate and gravel or crushed rock as coarse aggregate.

2.2.3 Original Concrete

Concrete from reinforced concrete structures, plain concrete structures or precast concrete units, which can be used as a raw material for the production of recycled aggregates (or for other useful purposes). Original concrete can refer to demolished concrete or conventional concrete.

2.2.4 Recycled Aggregate Concrete

Concrete produced using recycled aggregates or combinations of recycled aggregates and other aggregates. Recycled aggregate concrete is denoted by RAC.

2.2.5 Original Mortar

Original mortar is a hardened mixture of cement, water, and conventional fine aggregate in original concrete. Some original mortar is always attached to particles of original aggregate in recycled aggregates. Original mortar can be referred to as conventional mortar.

2.2.6 Original Aggregates

Original aggregates are conventional aggregates from which original concrete is produced. Original aggregates are natural or manufactured, coarse or fine aggregates commonly used for the production of conventional concrete. When no misunderstanding is possible, original aggregates may also be referred to as virgin or conventional aggregates.

2.2.7 Recycled concrete aggregates

Aggregates produced by the crushing of original concrete; such aggregates can be fine or coarse recycled aggregates. Fine recycled aggregate is sometimes referred to as crushed concrete fines. When no misunderstanding is possible, recycled concrete aggregates may be referred to as recycled aggregates.

2.3 Definition of Pavement Types and Components

Highway pavements are divided into two main categories: rigid and flexible. The flexible wearing surface of rigid pavement is usually constructed of Portland Cement Concrete (PCC) that acts like a beam over irregularities in the underlying supporting material. The wearing surface of flexible pavements, on the other hand, is usually constructed of bituminous materials that remain in contact with the underlying material even when minor irregularities occur [4].

Flexible pavement may consist of a relatively thin wearing surface built over a base course and subbase course, and they rest upon the compacted subgrade. In contrast, rigid pavements are made up of Portland Cement Concrete (PCC) and may or may not have a base course between the pavement and subgrade [5].

Figure 2.1 shows the components of a flexible pavement consisting of the subgrade or prepared roadbed, the subbase, the base, and the asphalt concrete surface. The performance of the pavement depends on the satisfactory performance of each component, which requires proper evaluation of the properties of each component separately.

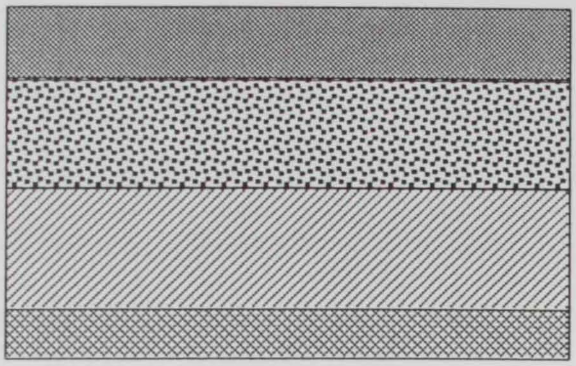


Figure (2.1): Schematic Diagram of a Flexible Pavement

2.3.1 Subgrade (Prepared Road Bed)

The subgrade is usually the natural material located along the horizontal alignment of the pavement and serves as the foundation of the pavement structure. The subgrade may also consist of a layer of selected borrow materials, well compacted to prescribed specifications. It may also be necessary to treat the subgrade material to achieve certain strength properties required for the type of pavement being constructed.

2.3.2 Subbase Course

The subbase component is located immediately above the subgrade and consists of material of a superior quality to that which is generally used for subgrade construction. The requirements for subbase materials are usually given in terms of the gradation, plastic characteristics, and strength. When the quality of the subgrade meets the requirements of the subbase material, the subbase component may be omitted. In cases where suitable subbase material is not readily available, the available material can be treated with other materials to achieve the necessary properties. This process of treating soils to improve their engineering properties is known as stabilization.

2.3.3 Base Course

The base course lies immediately above the subbase. It is placed immediately above the subgrade if a subbase course is not used. This course usually consists of granular materials such as crushed stone, crushed or uncrushed slag, crushed or uncrushed gravel, and sand. The specifications for base course materials usually include stricter requirements than those for subbase materials, particularly with respect to their plasticity, gradation, and strength. Materials that do not have the required properties can be used as base materials if they are properly stabilized with Portland cement, asphalt, or lime. In cases, high quality base course materials may also be treated with asphalt or Portland cement to improve the stiffness characteristics of heavy-duty pavements.

2.3.4 Surface Course

The surface course is the upper course of the road pavement and is constructed immediately above the base course. The surface course in flexible pavements usually consists of a mixture of mineral aggregates and asphaltic materials. It should be capable of withstanding high tire pressures, resisting the abrasive forces due to traffic, providing a skid resistant driving surface, and preventing the penetration of surface water into the underlying layers. The thickness of the wearing surface can vary from 3 in. to more than 6 in., depending on the expected traffic on the pavement.

2.4 Waste Disposal and Material Recovery

Before discussing RCA in detail, it's important to have a general idea about conventional disposal operations and recovery of materials.

2.4.1 Conventional Disposal Operations

Refuse disposal has been carried out according to one of three basic methods [6]: "sanitary landfill, incineration, or composting. Sanitary landfilling, permanently placing refuse under maximum density in the earth with daily cover, is the predominant method wherever sufficient land is available at low cost near the sources of waste generation.

Where land is not available at economical prices within reasonable distances from the centers of refuse generation, central incineration presents distinct advantages. In fact, because of the small land requirements and apparent weight (and volume) reduction possible with incineration, municipal incineration has been the usual method of refuse disposal in most large cities for several decades. Despite the ever more stringent air quality standards, which are being applied to incinerator effluents and the consequent increasing control costs, incineration still must be considered feasible and economically attractive in many situations.

Composting, the aerobic degradation of waste, is not practiced to any significant degree in the United States because of the relative availability of arable land and the abundance of inexpensive fertilizers in North America. With impetus for resource recovery coming from all strata of society, composting may be attempted with more frequency in the future. Certainly aerobic decomposition of degradable waste constituents could be a valuable adjunct to other methods of refuse management [6]". Concrete waste can be managed by only the first method of disposal, which is landfilling, as mentioned above.

2.4.2 Material Recovery

A visitor to a sanitary landfill or to the storage area of a municipal incinerator is generally appalled at the sight of so much material being wasted. Municipal waste amounts to approximately 200 million tons per year in the United States alone. In addition to municipal waste, industrial solid wastes which is generally collected and partially recycled "in-house" amounts to at least as much material as the municipal refuse. Overshadowing waste in both of these categories is the amount of waste generated each year in agriculture, over a billion tons in the United States alone. Finally, the real giant of waste producing activities is mineral extraction; almost 1-½ billion tons of ore waste are generated each year in the continental United States [6].

When the finite limits of mineral resources are considered, and when the above-mentioned amounts of solid waste are surveyed, the inevitable question arises "How much of this waste can be saved and recycled?" A great deal of the material in the solid waste stream is potentially recoverable, and an intensive search is underway for feasible and practicable materials recovery systems. To date, the success of materials recovery efforts has been accompanied by dismal failures in attempts to reuse other waste materials [6].

The materials which can be recovered from solid wastes (secondary materials) may be categorized into two general groupings: those materials which can be directly recycled, directly put back into use; and those materials which require considerable amounts of processing before they can be reused. An example of waste which may be directly recycled is the in-house glass waste produced during the manufacture of clear milk bottles. This glass waste, called cullet, may be collected and reinserted into the primary furnace in a glassmaking operation with no detrimental effects. On the other hand, a newspaper which travels to a consumer and hence into the solid waste stream must first be separated from the remainder of the refuse, then shredded and physically manipulated to separate individual fibers, processed in a deinking mill, and finally returned to a papermill for reuse. Obviously, it is much easier to recycle glass cullet than to recycle newspapers. Because of the ease of reuse of in-house wastes mentioned in the previous paragraph, most of the secondary materials recovered today are retrieved as a result of direct recycling programs. In other words, industry recycles in-house wastes [6]".

2.5 Municipal Solid Waste (MSW)

Carra and Cossu [7] prepared some information about the amounts of MSW generated in several countries and the mix methods currently used to manage MSW in these countries. Table 2.1 presents a summary of these data in terms of the totals generated in the country as well as per capita generation rates. One thing that is evident from this table, especially the footnotes, is that countries are not necessarily using the same definition of MSW. With there being no generally accepted definition between, and probably even within countries, there is no right or wrong definition. But as more research is done into waste management, it will become more and more important to have generally accepted definitions for this and other terms. However, based on the figures given, for fifteen reporting countries the median of per capita generation is around one kilogram per person per day; that is, half of the countries report values less than that and half report more [7].

Table 2.1. Municipal Solid Wastes: Amounts Generated by Country (reference N0.7)

	Amounts generated	
Country	Totals (10^6 t / year)	Per capita (kg/person/day)
Austria	1.7	0.6
Canada [1]	25	2.7
Denmark [2]	1.3 – 3.4	0.7 – 1.8
Finland	2 – 3	0.5 – 1.6
France [3]	17.8 – 49.8	0.9 – 2.5
FRG	24	1.1
Italy	17.3	0.8
Japan	41	0.9 – 1.1
Netherlands [4]	8.5	1.6
Poland	-	0.6 – 1.3
South Africa	12	1.0
Sweden	2.5	0.8
Switzerland	6.3	2.6
UK	18	0.9
USA	72	1.6

1 Figures only available for municipal and industrial/commercial combined.

2 Household waste – household plus commercial plus bulky.

3 Household wastes – household plus industrial waste that is similar to household wastes.

4 Household, road sweep, etc., office/shop/service wastes combined.

Table 2.2 summarizes the mix methods currently being used to manage MSW in each of the reporting countries. The mix varies widely, with sanitary landfilling handling only 20-30% of MSW in Switzerland and Japan, while in Finland, Canada and Poland 95% or more of the MSW is landfilled.

Table 2.2. Percent of MSW Managed by Different Methods (reference No.7)

Country	Landfilled	Incinerated	Recycled	Composted	No service
Austria [1]	64	20	-	16	-
Canada	95	4	1	-	-
Denmark	31	50	18	1	-
Finland	95	2	3	-	-
France	47.9	41.9	0.6	8.7	-
FRG	74	24	-	2	-
Italy	83.2	13.9	0.6	2.3	-
Japan [1]	29.6	67.6	-	2.8	-
Netherlands	51	34	15	-	-
Poland	99.9 [2]	-	-	0.1	-
SouthAfrica [3]	69.2	20.8	3.1	3.8	3.9
Sweden	35	60	5 [4]	-	-
Switzerland	20	80	-	-	-
UK	88	11	1.0 [5]	-	-
USA	83	6	11	-	-

1 Figures do not take recycling into account.

2 Includes wastes disposed of in controlled and uncontrolled dumps; less than 1% of the dumps are true sanitary landfills.

3 225 of 564 landfills are uncontrolled.

4 Separation/composting plants.

5 Mostly waste-derived fuel.

The most popular competing technology is, of course, incineration. Around the turn of the century, the first of the Municipal Waste Combustors (MWC) for energy recovery was built in Europe, and Europe led the world in the further development of this technology. In recent years, Japan has become one of the leaders in the use of this technology with almost 68% of MSW incinerated. The choice of this technology in Japan as well as other countries has been primarily driven by limited land availability [7].

2.6 Waste Concrete

2.6.1 Sources of waste concrete

Waste concrete can be produced from a number of different sources. The most common are demolition projects. Many concrete structures like buildings, bridges, sidewalks, and roads are razed after a period of time into their service life for purposes of replacement or landscape changes. Other sources of waste include: natural disasters like earthquakes, avalanches, and tornadoes; human causes like war and bombing; and structural failures. All these contribute to vast quantities of waste concrete that must be managed in some way [8].

2.6.2 Quantities of waste concrete

The use of crushed concrete waste as concrete aggregate began in Europe at the end of World War II. It has been estimated that over 25 million tons of building rubble become available each year [9]. In the past, such wastes were being used as landfill or riprap.

The actual amount produced will vary from place to place, but the following provides an indication of the quantities [8]:

- In Japan, about 25 million tons of waste concrete were produced in 1990. This amount rose to 71 million tons per year by 1995 and is expected to be as high as 110 million tons per year by 2001;
- In Western Europe, about 0.7 to 1 ton per inhabitant is produced yearly; and
- In the United States, the amount of waste concrete produced is roughly 40 to 50 million tons per year.

2.7 The current practice of RCA

Currently, the major markets for recycled aggregates as indicated by Banthia and Chan [8] are in:

1. General bulk fill;
2. Base or fill in drainage projects;
3. Subbase or surface material in road construction; and
4. New concrete manufacture.

In particular, recycled aggregates have seen their greatest use in the construction of pavements. This is because crushed concrete has a number of properties that match those needed for such applications, and the process is easy and economical. For instance, the pavement concrete to be crushed is usually in the exact place where the new pavement will be constructed. This saves on the quarrying and transport costs. Besides, concrete from pavements tends to be more or less consistent in quality and free from contaminants, especially other building materials. Moreover, failure of a concrete pavement does not have the same potential consequences, including the possibility of loss of life, as does the failure of concrete in a structure. Crushed concrete pavements have been used as subbase or base course material, in bituminous mixtures, as a filter material, and as low quality stabilization/filler material in the construction of new pavements. There are also other minor applications for recycled aggregates, such as fill for breakwaters and levees, rip rap, ballast, roofing granules, neutralizing beds, filtration beds, thermal reservoirs, sound barriers, masonry, and cat-litter boxes [8].

2.8 Use of Waste Material in Highway Construction

The paper of Collilns and Ciesielki [10] presents an overview of a synthesis of highway practice study being sponsored by the Transportation Research Board (TRB) on the use of waste materials in highway construction. Included with a summary of the various types of waste materials, their availability, and how they have been used in highway construction and/or maintenance activities.

The authers identify various waste materials and by-products, which have been investigated or utilized in highway construction and the extent to which such materials have been used by state transportation agencies. Quantities, locations, characteristics, and prospective uses are discussed for about 25 types of waste materials and by-products. They also classify these waste materials or by-products as agricultural, domestic, industrial or mineral waste. Table 2.3 shows the use of waste material and by-product questionnaire responses by state departments of transportation.

Table 2.4 presents a breakdown of the annual generation of all solid wastes in each of the four categories. This study shows that a number of states have also used reclaimed concrete pavement or broken concrete, either as a road base aggregate, lean concrete base, embankment material, or the coarse aggregate fraction of new concrete mixes. In the recycling process, steel is removed and the reclaimed concrete is crushed and screened to a desired sizing. The use of recycled coarse aggregate has no significant effect on the mixture proportions or the workability of concrete. When used as fine aggregate, mixes are less workable and require more cement due to water demand. Recycled fines are usually limited to a maximum of 30 percent of the sand portion of the mixture [10].

Table 2.3. Use of Waste Materials and By-products as Indicated from Questionnaire Responses by State Departments of Transportation (reference No.10)

Waste Material	No. of States Using	Waste Material	No. of States Using
Reclaimed Asphalt Pavement	42	Incinerator Ash	5
Coal Fly Ash	42	Paper Waste	5
Scrap Tires	38	Demolition Rubble	5
Iron and Steel Slags	18	Foundry Waste	5
Reclaim Concrete Pavement	16	Used Motor Oil	5
Coal Bottom Ash	14	Quarry Waste	4
Scrap Plastic	14	Sewage Sludge	3
Broken Concrete	11	Sulfate Waste	3
Kiln Dusts	10	Silica Fume	3
Mining Waste	9	Roofing Shingle	2
Waste Glass	9	Non-Ferrous Slags	2
Wood Waste	9	Compost	2

Table 2.4. Classification and Annual Generation of Waste Materials and By-products [Millions of Tons per Year] (reference N0.10)

	Annual Quantity
Agricultural Wastes	**2100**
Animal manure	1600
Crop wastes	400
Logging and wood wastes	70
Miscellaneous organic wastes	30
Domestic Wastes	**200**
Household and commercial waste	185
Municipal incinerator ash	
Waste glass	
Reclaimed plastic	
Sewage sludge	8
Compost	2.5
Scrap tires	2.5
Used oil	2
Industrial Wastes	**400**
Coal ash (fly ash and bottom ash)	72
Ferrous and non-ferrous slags	34
Reclaimed paving materials	103
Construction and demolition debris	25
Cement and lime kiln dusts	24
Sulfate waste	18
Lime waste	2
Roofing shingle waste	8
Foundry wastes	10
Ceramic wastes	3
Silica fume	1
Mineral Wastes	**1800**
Waste rock	1020
Mill tailings	520
Coal refuse	120
Washery rejects	105
Phosphogypsum	35

Total Annual Solid Waste Generation = 4.5 billion tons/yrs

In another study, a questionnaire was developed and distributed to all the state highway agencies, in order to obtain information on the current practices in the United States in the use of waste materials in highway construction [11]. Some of the results of the survey questionnaire are summarized in Tables 2.5 and 2.6.

Table 2.5 tabulates the waste products and their applications in highway construction showing the total number of the responders who have reported their use for various applications. Table 2.6 presents the evaluation of various waste products from technical, economic, and environmental standpoints as reported by the respondents. This study is concerned about the recycling of paving materials and the building rubble.

2.8.1 Recycling of paving materials

The recycling of paving materials includes the recycling of asphalt pavement and the recycling of concrete pavement. The technology for the use of reclaimed paving materials is fairly well developed and it is currently the most widely used waste product. Recycling of Portland cement concrete (PCC) is technically and economically viable, and results in a positive impact on the environments. Potential problems include cracking of recycled concrete pavements [11].

2.8.2 Building rubble

Properties and economics of using building rubble in highway construction depend on the nature and type of source, and also the local conditions. Limited past experience and research indicate that roofing waste is economically and technically feasible for

Table 2.5. Summary of Waste Material and Their Current Uses in the United States Highway Industry (reference No.11)

Waste Material	No. of States Using the Material[1]	Material is Used as Additive to[2]:				Material is Used as [2]:				Landscaping (see 2)	Others (see2,3)
		Wearing Course	Base	Subbase	Subgrade/ Embankment	Wearing Course	Base	Subbase	Subgrade/ Embankment		
Reclaimed Paving Materials	41	23	26	14	5	8	16	8	5	-	3 (sh)
Coal Fly Ash	31	20	5	6	4	1	2	-	2	-	9 (cc), 1(us)
Rubber Tires	29	21	6	1	2	-	1	-	3	-	11 (cs)
Blast Furnace Slag	15	4	2	-	-	3	5	3	2	2	4 (cc), 1 (sb)
Steel Slag	9	4	2	1	-	1	2	-	2	1	1 (ic)
Coal Bottom Ash	7	2	2	1	1	-	1	1	1	-	3 (ic), 1 (sc)
Used Motor Oil	7	-	-	-	1	-	-	-	-	-	3(recy),3(apf)
Boiler Slag	7	4	1	-	-	-	1	1	1	-	3 (ic), 1 (sc)
Waste Paper	6	-	-	-	-	-	-	-	-	5	1 (recy)
Mine Tailings	5	-	-	-	-	-	-	-	5	-	-
Sewage Sludge	4	1	-	-	-	-	-	-	-	1 (sa), 2(c/f)	-
Building Rubble	3	-	1	1	-	-	-	-	1	-	-
Waste Glass	2	1	2	-	-	-	-	-	-	-	-
Sawdust	2	-	-	-	-	-	-	-	2	-	-
Ceramic Waste	2	1	1	1	-	-	-	1	1	-	1 (pb)
Incinerator Residue	2	2	1	-	-	-	-	-	-	-	-
Highway Hardware	2	-	-	-	-	-	-	-	-	-	2 (recy)
Foundry Waste	1	1	1	-	-	-	-	-	-	-	-
Scrubber Sludge	1	-	-	-	-	-	-	-	1	-	-
Phosphate Slag	1	1	-	-	-	-	-	-	-	-	-
Straw	1	-	-	-	-	-	-	-	-	1	-
Plastic Waste	1	1	-	-	-	-	-	-	-	-	-
Lime Kiln Dust	1	-	-	1	1	-	-	-	-	-	-

Notes:
1. Of the 42 states who responded to the questionnaire.
2. The number under each column shows the total number of states that currently use the material in the respective application.
3. Abbreviations used: sh-shoulders, cs-crack sealer, cc-plain/structural cement concrete, us-under seal, ic-ice control, sc-seal coat, sb-sand blasting, recy-recycling, apf-asphalt plant fuel, pb-pipe bedding, f-fertilizer, c-compost, sa-soil aeration.

Table 2.6. Evaluation of Waste Products from Technical, Economic, and Environmental Factors (reference No.11)

Waste Materials	Total States	Economic				Performance					Environmental				
		Evaluation by	Cost Eff.	Equal	Uneconomical	Evaluation by	Very Good	Good	Satisfactory	Poor	Evaluation by	Good	Satisfactory	Not Acceptable	Doubtful
Reclaimed Paving Materials	41	31	19	12	-	34	2	15	17	-	33	15	14	-	4
Fly Ash	31	22	15	7	-	24	1	13	10	-	26	12	13	-	1
Rubber Tires	29	15	3	4	8	19	3	5	5	6	21	8	11	-	2
Blast Furnace Slag	15	11	5	6	-	11	3	5	3	-	11	2	7	1	1
Steel Slag	9	3	1	1	1	5	1	2	1	1	5	1	3	-	1
Bottom Ash	7	3	2	1	-	5	1	3	1	-	4	2	2	-	-
Used Motor Oil	7	3, recycle; 3, use as fuel for asphalt plant (concern expressed about adverse effects on air quality); 1, additive to subbase.													
Boiler Slag	7	3	1	1	1	3	1	2	-	-	3	1	2	-	-
Waste Paper	6	2, recycle; 4, use for landscaping as mulch.													
Mine Tailings	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sewage Sludge	3	1	-	1	-	1	-	-	1	-	1	-	-	-	1
Building Rubble	2	1	1	-	-	-	-	-	-	-	1	-	1	-	-
Waste Glass	2	1	-	-	1	-	-	-	-	-	1	-	1	-	-
Sawdust	2	1	1	-	-	1	1	-	-	-	1	-	1	-	-
Ceramic Waste	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Incinerated Residue	2	-	-	-	-	-	-	-	-	-	1	-	-	1	-
Highway Hardw.	2	2, recycle. (Highway Hardware)													

Notes:

1. Of the 42 states who responded to the survey questionnaire of this study.
2. The waste products whose use is reported by only one state highway agency are as follows: Foundry Waste, Phosogypsum, Recycled Steel in Rebar, Ground Shingle Manufacturing Scrap, Scrubber Sludge, Phosphate Slag, Atmospheric Fluidized Bed Combustion (AFBC), Plastic Waste, Straw, and Shredded Wood.
3. The information given in this Table is provided by the state highway agencies, based on their experience in the use of waste products, in response to the survey questionnaire of this study.

use in asphalt paving mixes. Building rubble has some potential for use as a material in subgrade, embankments and even subbase. However, the product needs to be contamination free and applicable for highway construction. Table 2.7 shows a recommended plan for the use of waste material in highway construction [11].

2.9 Portland Cement Concrete Pavement (PCCP)

Various studies have been carried out on the recycling of PCCP. Cross [12] et al. participated in a recycling PCCP project by recycling a moderately D-cracked concrete pavement and monitoring the performance over a 10-year period. The Recycled Concrete Pavement (RCP) aggregate was evaluated in four test sections consisting of two control sections, one test section of Portland Cement Treated Base (CTB) with RCP aggregate, and one test section using RCP aggregate in the PCCP and CTB. A Hot Mix Asphalt (HMA) shoulder using RCP as coarse aggregate was also constructed. The test sections were monitored over a 10-year period for performance including faulting, roughness, load transfer, and friction measurements. Faulting, roughness, performance level, and joint distress measurements from Kansas Department of Transportation (KDOT) 1995 pavement condition survey were used to compare the performance of the recycled sections with PCCP of similar age and traffic in the same area of the state. All test sections performed well, with the CTB and PCCP sections with RCP aggregates showing slightly more distress [12].

State highway agencies in Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming have successfully designed and constructed rigid pavements containing RCA as stated by the study of Cuttell [13] et al. Success has been attributed in part to the

Table 2.7. Recommended Plan for the Use of Waste Materials in Highway Construction (reference N0.11)

Waste Materials	Recommended Priority of Applications	Potential Problems/Research Areas
Reclaimed Paving Material	1) Recycling of asphalt pavements; 2) Recycling of Portland cement concrete pavements.	1) Is cost effective and economically feasible, air pollution is a potential problem; 2) Recycled PCCPs have experienced cracking, which need to be further researched.
Coal Fly Ash	1) Additive to PCC pavements; 2) As a fill material in embankment.	1) Guidelines and procedures are fairly developed, only recommended for no critical pavement structures, further research is required for use in PCC slabs, bridge decks etc.; 2) Limited experience in this application, need to be further researched to determine properties of Indiana ashes and its effects on environments.
Blast Furnace Slag	As an aggregate in highway construction.	Is technically and economically feasible, properties vary with type of source, some concern over leachates, properties of Indiana slags and effects on environments need to be determined.
Coal Bottom Ash / Boiler Slag	As an aggregate in highway construction.	Is technically and economically feasible, but may be potentially corrosive, field evaluations are required to develop correlations of laboratory results with field performance.
Steel Slag	As an aggregate in highway construction.	Is technically and economically feasible in asphalt pavements, potentially expansive when exposed to moisture, leachate analyses to determine environmental acceptability are required.
Rubber Tires	1) Crack/joint sealant; 2) As Stress Absorbing Membrane (SAM); 3) Soil reinforcement; 4) As lightweight aggregate in embankments; 5) As Stress Absorbing Membrane Interlayer (SAMI). 6) As overlays/wearing courses in asphalt pavements.	1) Has generally performed better than conventional materials, long-term performance need to be evaluated; 2) Reduces reflection of cracking, costs more than the conventional surface treatments, has generally given longer service life, further evaluation is required to determine performance and cost effectiveness over life cycle; 3) Is beneficial as large quantities of tires can be consumed and results in considerable savings in earth fill, leachates have adverse effects on environments; recommended for use only in unsaturated zone, further evaluations are required to develop standard designs and ascertain environmental consequences and economic benefits; 4) Beneficial since nonbiodegradable, leachate problem, recommended to be used in unsaturated zone; 5) Reduces reflection of cracking, is uneconomical; 6) Experience indicates both failures and successes, costs 50% to more than 100% higher than conventional materials, longer life has generally not been substantiated by field performance, concern over air pollution, further research is required to assess performance, environmental acceptability, develop mix design specifications and construction procedures, and feasibility for recycling.
Waste Glass	1) As an aggregate in unbound base layers and as a fill material in embankments; 2) As an aggregate in asphalt pavements; 3) As and aggregate in PCCPs.	1) Contamination free glass is technically feasible if it meets INDOT gradation specifications, economics depend on local conditions; 2) Is uneconomical, potential problems include: separation at the asphalt/glass interface and subsequent raveling under studded tires, and maintenance of adequate skid resistance; 3) Is not suitable in PCCPs due to likelihood of alkali-silica reactions
Incinerator Residue	As an aggregate in highway construction.	Limited experience/research, leachates may contaminate groundwater, further laboratory research is needed to assess economic, technical, and environmental feasibility.
Building Rubble	1) Use of roofing waste in asphalt pavements; 2) As an aggregate in highway construction	1) Is technically feasible, if the source is contamination free, economics depend on the local conditions; 2) Potentially suitable as a fill material in subgrade/embankment and even in subbases, if it is contamination free.
Sewage Sludge	1) Compost and co-compost; 2) Incinerator ash from sludge as an aggregate in highway construction.	1) Likelihood of some health risk to individuals applying this products and also concern over undesirable leachates; 2) Limited experience, is economical in some areas, environmental concerns have been expressed over leachates, further research is required to assess its feasibility.
Waste Paper*	1) Recycling; 2) As mulch for landscaping.	Both applications are feasible, recycling is more beneficial.
Used Motor Oil*	1) Recycling; 2) Fuel in asphalt plants.	1) Is beneficial; 2) Environmental concern over air pollution.
Highway Hardware*	Recycling.	Is economically beneficially.
Mine Tailings*	As an aggregate in highway construction.	Feasibility depends on source which need to be evaluated from economic, technical, environmental factors.
Sawdust*	As a lightweight fill material in embankments.	Biodegradable, service life may be less, gives better performance if used in saturated zones as it is likely to reduce decay of wood.

Notes: The priority of applications for various waste materials given in this Table is based on subjective assessment of the researchers.
* Not listed according to priority.

minimization of old mortar content in the RCA during recycling processes, thereby controlling the total content of the new Portland cement concrete mixture, or to the achievement of higher than expected compressive strengths through adjustments in mix proportions, or both. There was no clear correlation between mortar content and cracking distresses in field investigations, although one project did exhibit significantly more slabs cracking in the recycled pavement than in the corresponding control pavement. The increased cracking may have been due to large differences in total mortar content between the recycled and control sections [13].

The field evaluation indicates that five different state highway agencies successfully used recycled PCC in paving applications. Comparable pavement performance between recycled and conventional PCC pavements was especially common when there were similar amounts of natural aggregate in the PCC mixture. This condition occurs when crushing operations remove most of the old mortar from the original aggregate [13].

Load transfer efficiency can be linked to both joint or crack face texture and joint or crack width, and can be affected by the use of RCA, since the inclusion of old mortar affects PCC thermal expansion and contraction, PCC shrinkage, and crack face texture. Minimizing the inclusion of old mortar in the RCA product will decrease the potential for excessive slab expansion and contraction because as total mortar content decreases (recycled mortar plus new mortar in the PCC mixture), aggregate restraint increases and drying shrinkage and coefficient of thermal expansion decrease. Recurrent D-cracking was not observed in any of the surveyed projects. This was attributed to one or more of several factors (varying from case to case), including the use of fly ash in the recycled mixture, decreased availability of water, decreased aggregate top size, and possible exhaustion of the D-cracking mechanisms during the original performance period [13].

Another study was done by Hironaka and Shoemaker [14] and the objective of the study was to develop criteria and guidelines for recycling Portland cement concrete airport aprons. Included in this study are all aspects of the recycling process, including breakup and removal, steel reinforcement removal, crushing, screening, stockpiling, mix design, testing, placing, finishing, and performance. Recycling of PCC requires some specialized equipment such as pavement breakers and electromagnets for steel removal; however, all other equipment and procedures are those commonly used in the construction industry. Based on the regression experimental design procedure and laboratory tests conducted on pavement samples for six airports of widely varying age and conditions, it has been conclusively shown that aged PCC pavements can be recycled into new surface courses that meet strength requirements and have the same cyclic load carrying (fatigue) characteristics as those constructed with virgin materials. The optimum values for proportions that should be used in recycle mixes are: water/cement ratio (0.46), coarse aggregate content (58 percent), and virgin sand content (42 percent). Because the fines generated from the crushing of the old pavement degrade the strength of recycled concrete, their use is not recommended for recycled heavy-duty airport pavements [14].

Saraf and Majidzadeh [15] conducted another study to demonstrate the feasibility of using recycled crushed concrete from old pavements as aggregates in new PCC and asphalt pavements and to develop guidelines and criteria for making cost-effective decisions concerning the recycling of PCC pavements. This study included several activities such as: pre-construction evaluation of recycled PCC aggregates, construction monitoring and evaluation of mixes, post construction evaluation of mixes and data analysis. Four test sections, each approximately 1156 ft (349.3 m) long, were constructed on a roadway segment in Toledo area. Each lane of this four-lane road contained a PCC recycled aggregate section, PCC control section, Asphalt Concrete (AC) recycled aggregate section and AC control section. Cores of the old PCCP were obtained before their removal and tested in the laboratory. The aggregates from the crushed cores were then used to prepare trial mixes and measure the strength characteristics of the recycled mix. A crushing plant was designed and constructed at a quarry site to crush old pavements. This plant produced recycled aggregates for use in the mixes of test sections. Samples of recycled aggregates were used to design a mix for the construction of recycled PCC and AC test sections. The samples of concrete and asphalt mixes were collected during the construction. After the construction of all test sections, 32 cores from rigid pavement test sections and 24 cores from flexible test sections were obtained. These samples were also tested to determine various characteristics of concrete and asphalt mixes. Sixteen slabs out of a total of 216 slabs of recycled concrete mix developed transverse cracks at the mid-slab after 2 months of their opening to traffic. Based on the results of this study it was concluded that the use of recycled PCC aggregates in concrete mix is a feasible alternative. However, the use of the sand portion of recycled aggregates in concrete mix is not practical because this material has very high absorption compared to natural sand [15].

A study by Anon [16] reveals that if RCAs are substituted for virgin gravel in standard structural concrete mix designs, the same performance results cannot be guaranteed. Because RCA concrete contains both new mortar and old mortar from the recycled material, it has a higher coefficient of shrinkage. As a result, recycled concrete pavements can develop wider transverse cracks [16].

2.10 Properties of RAC

In order to find beneficial usage for such waste materials, several studies were carried out to study the properties of these materials. Rashwan and AbouRizk [17] studied the properties of concrete made with RCA and their sensitivity to the period of curing before crushing takes place and to the period of storage before use. The preliminary results indicate that the recovered material is usable and in certain cases may provide an advantage over natural aggregates. In particular, it was noted that strength improves if concrete was crushed and reused in a short period of time. The longer the storage of the concrete prior to crushing the less the strength gain, until it becomes comparable to that of concrete made with natural aggregates. Fresh concrete properties were also studied. In general, the recycled material produced harsher mixes with less workability compared to mixes made with natural aggregates [17].

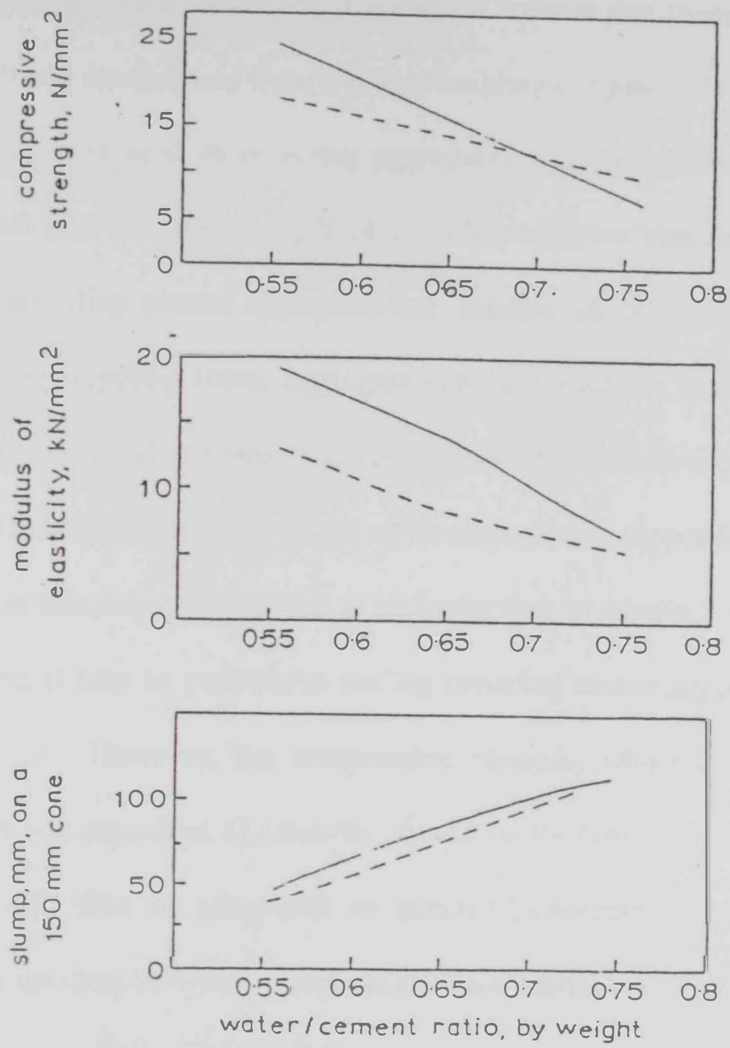
De Vries [18] discusses the need for recycled concrete giving examples of Dutch practice where replacement of 20 percent coarse aggregate giving C45 strengths is allowed. This amount does not affect the properties of fresh and hardened concrete. Replacement of up to 100 percent should give strengths up to C25 and cause no problems in concrete with minor constructive requirements. Environmental factors and large increases in the cost of waste disposal has led to investigations into the reuse of material and more efficient methods of disposal. Materials are separated at the demolition stage and rubble is produced from used concrete and masonry. Research has led to regulations for the requirements of the materials; crushed concrete aggregate must contain more than 95 percent of the material and crushed mortar must contain at least 65 percent. Not more than one percent may be of glass, wood, paper, textile etc.

According to the Dutch specifications, replacement of 20% of the coarse aggregate is allowed and application does not affect the properties of the fresh and hardened concrete. For many applications, larger replacements, up to 100% of the coarse aggregate, should cause no problems. Examples include concrete with minor constructive requirements, such as underwater concrete, site bases or site sealing and concrete for filling [18].

More and more studies have been carried out to determine the mechanical behavior of concrete containing pieces of broken concrete from demolition waste in the place of conventional natural aggregates.

A study on the proportioning and strength of recycled aggregate concrete by Swamy [9] indicated that while the compressive strength of concrete is reduced, along with higher moisture absorption, the bending strength is somewhat increased when broken concrete aggregates replace natural aggregates. It was also reported in the same study that recycled concrete aggregate loses its workability more rapidly than conventional concrete. This can possibly be explained by the fact that recycled concrete aggregate is more porous and thus more absorptive to water as compared to natural aggregates. Workability and mix proportions being the same, the compressive strength of RAC is at least 76% and its modulus of elasticity is not less than 60% that of conventional concrete. A comparison of the properties of recycled and conventional concrete is shown in Figure 2.2. The range of various properties of recycled concrete varies significantly with the mix proportion, type of cement, type and size of aggregates and water\cement ratio [9].

Another work by Inyang and Beergeson [19] presents results of an experimental study of recycled concrete prepared using crushed waste concrete as a part of the aggregate.



— Conventional concrete --- Recycled Aggregate Concrete

Figure (2.2): Typical Relationship Between Water/Cement Ratio and Various Properties of Recycled Aggregate Concrete

Compressive strength after freezing and thawing cycles, bonding of fresh mortar with waste concrete particles, and fracture characteristics of recycled concrete were compared with those of conventional concrete. The overall objective of the work was to evaluate the performance of crushed waste concrete for the purpose of substantial reuse in recycled concrete [19].

Two sources of waste concrete were obtained and crushed to produce the recycling fine aggregate and recycling coarse aggregate. One of the sources was from an earth-retaining wall (15 years old) and another was from a school building (25 years old). These two were mixed after crushing and used as recycling aggregates. In comparisons of compressive strength, it seemed that the low strength of recycled concrete was not because of the weakness of the recycling coarse aggregate, but because of poor bonding at the new interface between the recycling coarse aggregate and fresh mortar. The recycled concrete was experimentally evaluated in terms of fracture characteristics and compressive strength after freezing and thawing treatment. Some of fracture-related properties of the recycled concrete prepared in this study were found to be better than or identical with conventional concrete. Therefore, it may be possible to use the recycling coarse aggregate in structural concrete manufacture. However, the compressive strength, which is one of the most important load-carrying capacities of concrete, should be improved for practical use. The recycled concrete will then be acceptable as structural concrete. Improving the bond strength at the new interface between waste concrete and fresh mortar is suggested as a way of achieving better compressive strength [19].

Experimental work by Tavakoli and Soroushian [20] was conducted to determine the compressive, splitting tensile, and flexural strengths of recycled coarse aggregate concrete and to compare them with those of concrete made using natural crushed stone. The properties of the aggregate were also compared. The fine aggregate for recycled and conventional concrete was 100 percent natural sand. Two maximum sizes of aggregates, two levels of water/cement ratio, and two levels of dry mixing time of coarse aggregate were chosen to perform the experiments based on a full-factorial design. Test results indicate that the strength characteristics of recycled aggregate concrete are influenced by key factors, such as the strength of the original concrete, the ratio of coarse to fine aggregate in the original concrete, the ratio of top size of aggregate in the original concrete to that of the recycled aggregate, and the Los Angeles abrasion loss and water absorption of recycled aggregate. These factors also influence the effect of water/cement ratio, aggregate top size, and dry mixing on the strength characteristics of recycled aggregate concrete. It is also shown that the conventional relationships between splitting tensile, flexural, and compressive strengths may have to be modified for RAC. The final conclusion of this work is that through proper measures, high-quality concrete materials can be produced using recycled concrete aggregate. For this purpose, it is necessary to determine the properties of the original concrete, based on which realistic qualities can be targeted for recycled aggregate concrete [20].

Salem and Mohammed [21] also studied compressive strength and volume stability for mixes varying the water/cement ratio. The results are shown in Table 2.8.

Table 2.8. Comparison of 28-day Compressive Strengths of Conventional and Recycled Aggregate Concrete (reference No. 21)

Water-Cement Ratio	Compressive Strength N/mm^2	
	Conventional Concrete	Recycled Concrete
0.55	32.23	22.86
0.60	27.43	22.53
0.65	22.82	21.81
0.70	19.81	20.64
0.75	16.12	19.91

A compressive strength in the range of about 20 N/mm^2 was easily attainable. The recycled concrete at a water/cement ratio of 0.55 showed a compressive strength of 22.86 N/mm^2, which was about 27% lower compared to conventional concrete. Since the recycled concrete aggregate was more absorptive to water as compared to the natural aggregates, it was found to lose its workability quickly. There was not much difference in the slump values above 0.7, whereas at water/cement ratio of 0.6 the slump for recycled concrete was about 10-15% lower compared to that for conventional concrete, which had a slump of about 70 mm. Drying shrinkage for recycled concrete was about 15 to 20% larger than for concrete made with natural aggregates. Recycled concrete also showed up to 15% increase in the permeability value as compared to conventional concrete. From the results of this study the author believes that the recycled concrete produced from demolition concrete wastes has been found to be very suitable for base courses of pavements [21].

Ravidrarajag [22] discussed the results of a series of investigations into the properties of recycled concrete aggregates and the effects of using them on the properties of concrete. As said previously, concrete aggregates differ from natural aggregates due to the presence of a considerable proportion of mortar attached to the natural aggregates and consequently affecting the properties and performance of concrete. The results of Ravidrarajag [22] shows that for RAC, compressive and tensile strengths and modulus are reduced, whereas drying shrinkage and creep are increased. The effect of using concrete fine aggregate on the modulus and shrinkage is less than that produced by the use of concrete coarse aggregate. The strength of RAC can be recovered by making suitable mix adjustments or by the addition of fly ash or silica fume. Modulus of elasticity, drying shrinkage and creep cannot be fully recovered by the above methods although improvements were observed [22].

Properties of concrete made using RCA as coarse aggregate were investigated also by Olorunsogo [23]. He made five mixes using 26.5 mm maximum aggregate size and water/cement ratio of 0.5. A control concrete mix was prepared with 100% natural crushed coarse aggregate (NA) while another four mixes were made with RA at 30, 50, 70, and 100% replacement levels. The properties studied were workability and compressive strength; measured at 3, 7, and 28 days. The results showed that, in general, there was an improvement in the workability of the concrete mix (i.e. increase in slump value) with increases in the amount of recycled aggregate in the mix. As for compressive strength development, the general tendency was for reductions in compressive strength with increases in the proportion of RA in the mixes. At the age of 28 days, the highest compressive strength value of 36 Mpa was observed on the mix containing 100 % NA while the lowest value of 31 Mpa was obtained on the 100% RA mix. No specific trend could be observed in the other properties investigated. Nonetheless, the results indicate that there is potential for the use of RAC in the manufacture of concrete [23].

An experimental study by Masoud [24] et al. was conducted to assess the safe and economic use of concrete using demolished waste as a structural grade. In order to find out the optimum percentage of demolished waste for mixing in concrete to achieve desired strength and safety, cubes, cylinder and flexural specimens containing demolished waste as one of the components, along with such specimens of reinforced concrete for comparison, were cast and tested after 28 days of curing for their crushing strength, split tensile and flexural strength in the laboratory. It was found that workability of concrete decreases with an increase in the addition of demolished waste. The recycled concrete and recycled aggregate concrete with 20 percent respective replacement by demolished waste partially agreed with the behavior of conventional concrete, with only a marginal decrease in their crushing, split tensile and flexural strengths [24].

RAC can utilize demolition material from concrete and masonry constructions, as observed in this review. Several studies have been made on the reuse of concrete waste, but only limited studies have been made with respect to use of demolished brick masonry as aggregate. An attempt has been made by Ramamurthy and Gumaste [25] to assess the physical and mechanical properties of RCA for its suitability in concrete making and they study the strength and behavior of RAC using different types of demolition wastes. The compressive strength of recycled aggregate concrete is relatively low and the variation depends on the strength of the parent concrete from which the aggregates have been obtained. The range of compressive strengths obtained shows that recycled concrete of different mixes made with recycled aggregates obtained from [25]:

1. Demolished brick masonry can be used for manufacture of load bearing masonry units and plain cement concrete works, and
2. Demolished concrete aggregates can be used for both plain cement concrete and reinforced concrete.

Malhorta [26] has done one of the old RCA studies in 1978. He observed that large urban centers in Canada and the United States are finding it increasingly difficult to locate and develop natural aggregate sources for use in concrete. The study was therefore undertaken to investigate the possibility of producing aggregates from discarded concrete control test cylinders, normally sent to waste dumps after testing. A series of 2.2 ft^3 (0.062 m^3) concrete mixes were made covering the low, medium and high strength levels. Two sets of mixes were made at each strength level; one set consisted of a control mix and a mix made using coarse aggregate prepared from recycled concrete and reference fine aggregate; the second set consisted of a control mix and a mix using fine aggregate prepared from recycled concrete and a reference coarse aggregate. Cylinder and prism specimens were cast from each mix to determine mechanical properties of concretes at various ages and to study the durability of concrete after exposure to freeze-thaw cycling. The analyses of the test results have shown that satisfactory concrete can be made with aggregates prepared from RCA. At lower water/cement ratios, strengths of the two types of concrete are comparable. The durability of concrete made with aggregates prepared from RC is comparable to the durability of concrete made with reference aggregates [26].

An interesting study was conducted by Montgomery and Sturgiss [27]. The paper describes a laboratory based experimental project to examine the effect that cleanliness of recycled aggregate particles has on the fresh and hardened properties of concrete. Cleanliness of the aggregate particles relates to the amount of cement paste and mortar adhering to the surface of the aggregate. Concrete constituents were recycled from a cast block of concrete by breaking the concrete into manageable lumps and then crushing the rubble to differing degrees in a Los Angeles abrasion machine. The resultant aggregate particles were sorted visually into four cleanliness categories according to the amount of material adhering to the aggregate surface. Concrete mixes were made in constant proportions for the four recycled aggregate categories and a control mix containing freshly quarried aggregate. Properties of the plastic concrete were determined by measuring slump, VeBe time, mass per unit volume and air content. Cylinders were cast and unconfined compression testing was carried out at 7, 28, 56 and 90 days to determine compressive strength gain. Results indicate that as the level of cleanliness of the recycled aggregate particle decreases, workability, mass per unit volume and compressive strength decrease, whereas air content increases [27].

Effects of using recycled concrete of different qualities as coarse aggregate upon the strength and deformation of concrete are reported by Ravindrarajah and Jam [28]. Tests on the aggregates showed that the RCAs have lower specific gravity and higher absorption capacity than the original crushed granite aggregate. The resistance to mechanical action such as impact, crushing and abrasion for the RCAs is also lower. The effects of using RCAs instead of natural aggregates in concrete are: reduction in compressive strength up to 25%, reduction in modulus of elasticity up to 30%, improvement in dumping capacity up to 30%, and higher amounts of drying shrinkage and creep [28].

Even with such variation in properties, recycled concrete appears to be a reasonable substitute in regions where either natural aggregates are scarce or where there is a severe waste disposal problem. Waste concrete produced from demolition of concrete structures is a good alternative source for the production of concrete aggregates and it is accepted because the production of new concrete depends on the quality of them.

2.11 Regional Effects on Recycling Debris

Regional variations have a major impact on the willingness for recycling debris. This can be illustrated with two examples mentioned by Pauw and Lauritzen [29]. The first example describes the recycling situation in Belgium. Between Belgium's regions, Flanders and Wallonia, quite a number of differences are observed in relation to the use of recycled materials. In order to appreciate these differences it is necessary to realize that there is a distinct geographical difference between the regions (see Figure 2.3).

Furthermore, it should be realized that since the mid eighties the regions are autonomous to develop their own environmental and building policy and legislation.

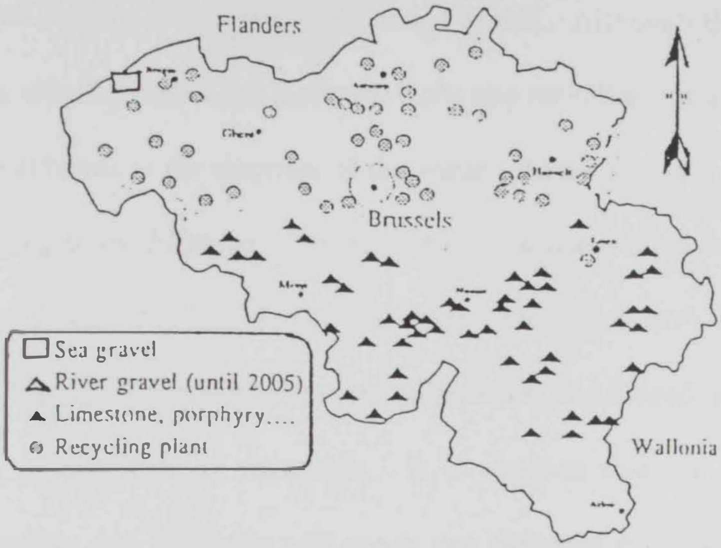


Figure (2.3): Map of Belgium

Flanders, which is situated in the North of Belgium, has a very high population density and nearly no natural aggregate resources are available. The production of construction and demolition waste has been calculated at 4.6 million tons per year, i.e. 807 kg per year per inhabitant. Tipping costs for building waste are typically in the range of 150 to 400 Belgian francs per ton. A high environmental tax of 350 Belgian francs per ton is added to this. At the end of 1992, new environmental legislation was introduced prohibiting the dumping of recyclable waste coming from construction and demolition. Taking this whole situation into account, it is quite logical that a well-established recycling industry is operating in Flanders and many new initiatives are currently going on.

Wallonia is situated in the South of Belgian and has a population density of only 190 inhabitants per square kilometer. A large number of quarries are dispersed over the territory. Estimates indicate a production of about 2 million tons of construction and demolition waste per year, i.e., 625 kg per year and per habitant. Tipping costs are lower than Flanders and typically in the range of 80 to 300 Belgian francs per ton. An environmental tax of 150 Belgian francs per ton is added to this. Although the number of authorized dump-sites is very limited at the moment. Only one recycling plant is operating. Obviously this leads to problems in the disposal of the waste. As a result of this situation a cooperation has been set up to establish an adequate network of dump sites for inert waste and the exploitation of stock sites for non-contaminated excavated soil (soil banks). Further, it aims at landscaping existing unauthorized dump-sites and closed quarries. The promotion of recycling is also one of the goals. It is obvious that the geographical differences between Flanders and Wallonia will result in a different economic interest in recycling between the regions.

A second example is a Danish feasibility study on the recycling of building waste in Kuwait in 1990. Kuwait has a production of 3 million tons of construction and demolition waste and expects at least an equally large annual quantity for the coming 10 years. This large pile of annual building waste causes a disposal problem for Kuwait. Until now this waste has been disposed of in landfill and, what is worse, disposed of by fly-tipping in the desert along roads and in unsuitable gravel pits. The total amounts of waste suitable for crushing and recycling was assessed to be close to 1.1 millions tons a year. However, in Kuwait it is not possible to finance a recycling project through taxes and tipping charges. Because of the enormous space available, the tipping charges at the landfills are minimal, and transportation costs are totally decisive in the choice of the disposal place. Therefore any recycling initiative in Kuwait must compete with similar products on the market. So it is necessary to aim at a high quality, which results in high demands on the machinery and operation. Fortunately, natural gravel aggregates of good quality are scarce and thus prices are high, making recycling feasible [29].

Where in the UAE the situation is similar to Kuwait except for the material which is available at normal prices, that's why the UAE government is still not thinking to use recycled concrete aggregates.

2.12 Damaging Disaster and Concrete Recycling

There are only very few examples of recycling projects in connection with larger site clearance and reconstruction projects following a damaging disaster. However, two interesting projects are reported below as stated by Pauw and Lauritzen [29].

The first project is a pilot recycling operation that was developed by the Belgian Building Research Institute (BBRI) after a violent earthquake in El Asnam (Algeria) in 1980. The goal was to investigate the possibilities of recycling building debris into new concrete building blocks. The project illustrated the feasibility of recycling debris in situ. The second project concerns the installation of a recycling plant in Leninakan (Armenia) by the German Red Cross to help with rehabilitation after the earthquake in 1988. It gives a good idea of the problems that accompany an intervention for recycling and reconstruction. The recycled aggregates were mainly used for road works.

2.12.1 El Asnam Earthquake (Algeria 1980)

The main shock had a force of 7.3 on the Richter scale and was followed three hours later by an aftershock with a force of 6.0. After two main shocks, a very large number of relatively heavy aftershocks followed. These were responsible for aggravating the damage to the buildings. After the earthquake the Algerian control authority made a thorough investigation of no less than 6538 constructions in the devastated area of El Asnam. To gain a picture of the total damage in El Asnam the assessment data were completed using aerial photographs of the area.

In view of the potential for recycling, the damage to buildings was obviously of most interest. Considering the seismic activity in the area it seemed prudent to repair only those buildings which sustained only minor damage, so that repairs could offer sufficient guarantee of further stability in the earthquake zone. In this respect the surveyed buildings could be subdivided into three groups as follows. A little over one third (35 %) of the buildings examined were simply recoverable with no or minor non-structural damage. Almost the same number of buildings (38 %) were destroyed or had to be demolished because of severe structural damage. The remainder (about 27 %), with minor damage to the whole of the building and only minor structural damage, was considered reparable. One of the remarkable features was that higher buildings were the most damaged. Of the buildings with 4 storeys (ground floor + 3) or more, more than 65 % had to be demolished. In order to gain a picture of the quantities of debris and of where this debris was located, one had, apart from the damage picture described before, to have data on the quantities and the categories of materials that were used in the different types of construction in El Asnam before the disaster.

The total quantity of materials used for El Asnam city was estimated at about 3 million tons spread over the different kind of materials (Table 2.9). The dwelling space alone represented approximately 1,440,000 tons of materials. Based on the qualitatively poor debris of El Asnam the production of structural recycled concrete had to be excluded, both on economical (separation techniques) and structural grounds (high requirements concerning the earthquake resistance). This and the great shortage of building blocks, not only in El Asnam, but also and in particular in the surrounding villages and rural areas, were two important reasons for choosing the fabrication of building blocks.

Table 2.9. Quantities of Materials Used in El Asnam City (reference No. 29)

Building Categories	Materials (tons)	
	Concrete (slabs included)	Mixed materials (concrete, bricks and concrete blocks)
I- Apartment buildings	230,000	190,000
II- Dwellings	-	1,020,000
III- Collective and industrial buildings	800,000	700,000
Total	1,030,000	1,910,000
General total	2,940,000	

In addition, the recycling of the debris also seemed economically favorable. On the one hand there was a great need for natural aggregates for the reconstruction; which had to be brought in from faraway places. Making the less demanding building blocks from recycled materials, and reserving the available natural aggregates for structural concrete, meant substantial savings on transport. On the other hand, the enormous quantities of debris did not need to be dumped, which was an additional restriction on the transportation requirements.

A first fragmentation of the debris was performed with sledge hammer and bulldozer. Afterwards the broken materials were fragmented to 0/25 mm in a secondary rotating crusher. The operation caused much dust because of the presence of brick masonry debris with plaster. Moreover, many of the fragments resulting from the bricks came out of the crusher in the form of lamellae. With the recycled aggregates thus obtained (Figure 2.4), six series of building blocks were made as shown in Figure 2.5, the composition of which are shown in Table 2.10.

The BBRI research on demolition and reuse of concrete and the pilot operation executed in El Asnam, have shown that such a recycling operation is possible. The results obtained were very convincing and proved that it was indeed feasible to recycle the debris as aggregates in concrete. However, although realistic, the project was halted because for both political and mainly sociological reasons, i.e. opposition of the local people to the use of debris, under which some of their beloved had died, as a construction material.

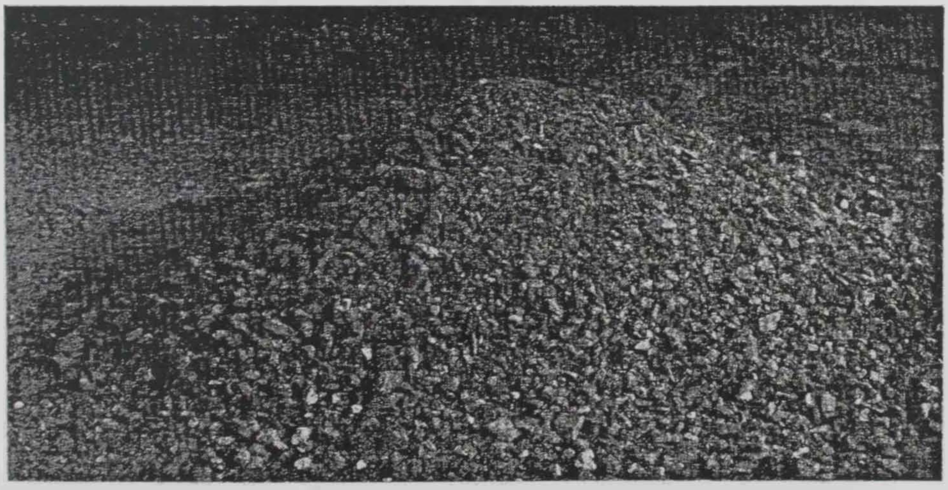


Figure (2.4): Recycle Aggregates

Table 2.10. Composition of the Building Blocks (reference N0. 29)

Series #	Batching (kg) (1)				
	Cement	Normal Sand	Natural Coarse Agg.	Debris	
				0 - 25	3 – 12
Preference	50	100	300	-	-
1	50	150	-	250	-
2	50	1000	-	200	-
3	50	200	-	200	-
4	50	150	-	-	300
5	50	150	-	-	250
6	50	200	-	-	200
(1) Composition for the manufacturing of 24 hollow blocks of 390 mm x 190 mm x 190mm					

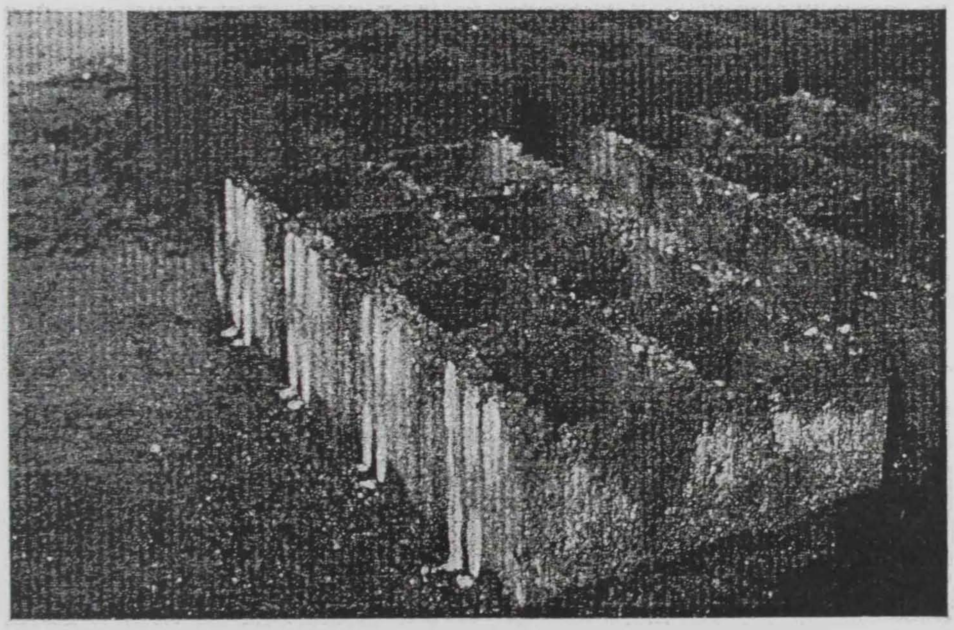


Figure (2.5): Recycled Building Blocks

Expert demolition, followed by a sufficient crushing capacity, could have resulted in over a million tons of recyclable material for the town of El Asnam, which roughly corresponds to some 50 million recycled building blocks. It would certainly have been an appropriate alternative to dumping several hundreds of thousands of tons of debris and the hauling over great distances of natural aggregates for the reconstruction of the town.

2.12.2 Leninakan (Armenia 1988)

This most recent example concerns the installation by the German Red Cross of a crushing plant in connection with the clearing and reconstruction work after the Armenian earthquake from December 1988. After this heavy earthquake, which destroyed more than 400 villages and caused 25,000 casualties and more than half a million homeless people, the German Red Cross ordered the installation of a recycling plant for debris, to support the suffering region of Leninakan.

The local conditions for installation were very difficult: 1600 meter altitude, severe winters, hot summers and heavy rainfall in spring and autumn, bad roads and transport conditions, insufficient water and electricity supply, etc. Another fact was that most of the debris (at the time of arrival of the recycling plant) was already transported and temporarily disposed of. This meant that the building debris was mixed with all kinds of waste, from household equipment to dead pets.

The plant was designed for a capacity of 120 ton/hr but achieved an output of more than 200 ton/hr and worked with no major problems. The produced construction material was primarily used for roadwork.

The whole installation covered a surface area of 13,700 m^2 and was able to resist new earthquakes practically no foundation was provided. The whole recycling-activity covered more than 30,000 m^2. The different successive working-phases that took place in the recycling process are as follows (Figure 2.6):

- From the 150 tons of debris that was transported to the plant every hour, 30 tons of wood, steel and other waste was separated. Thus the crushing operation was fed with 120 tons of debris every hour.
- Hydraulic scissors and hammers and transportable scissors reduced the dimensions of the concrete and stone debris to suit them for the first crusher.
- During the transportation to this crusher a workman sorted the impurities.
- After crushing, aggregates with a diameter from 0 to 50 mm were separated by sieving. Next, another workman sorted the debris again, before it was passed under magnets to separate the iron. Then the debris was temporarily disposed of.
- After the temporary disposal the debris was separated from the finest aggregates with a diameter from 0 to 4 mm. The rest was crushed again in a secondary crusher.
- Then again, the remaining iron was removed using magnets, before the remaining debris was separated in different fractions by two sieves. Granulates bigger than 45 mm were carried back to the secondary crusher.

2.13 Standards for Road Base Material in Dubai and Netherland

A consortium of Dubai authorities and Eerland Recycling Services was planning to establish a construction and demolition waste processing plant in Dubai. The Dubai Municipality (DM) exploits a landfill that contains a large quantity of this stony type of waste.

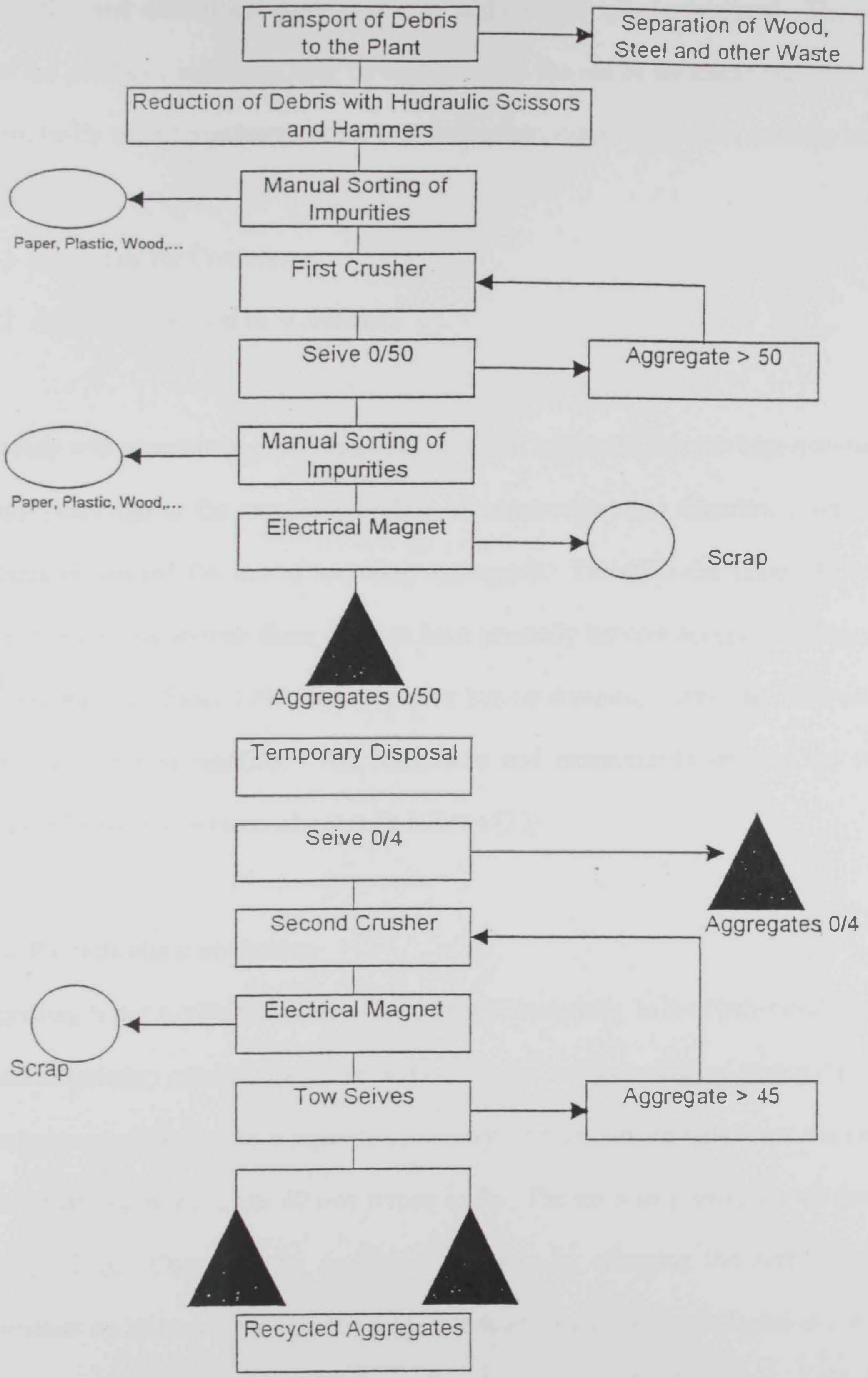


Figure (2.6): Recycling Plant of Leninakan (Armenia)

In order to reduce the need for landfill volume and to promote reuse and recycling of this construction and demolition waste, a sorting and crushing plant is planned. The practical use of the produced aggregate may be obstructed by the use of standards and requirements that originally were formulated for natural virgin aggregates. Two main sections have been produced:

1) Aggregate for Concrete
2) Aggregate for road base materials

This study will concentrate on the tests and results of aggregate for road base materials. Twenty years ago at the start of recycling of construction and demolition waste, Dutch standards obstructed the use of recycling aggregates. Therefore the standards had to be changed. In the mean-time these changes have generally become accepted and recycling is a normal practice. Since 1996 there is even a ban on dumping recyclable construction and demolition waste in landfills. The conclusion and recommendations for the study on aggregate for road base materials were as follows [30]:

2.13.1 Particle size distribution

The grading is not a critical parameter in road base materials. In the Netherlands the rubble is crushed (primary crusher) then screened on 40 mm and the oversized material is returned to the primary crusher or to a separate secondary crusher. In the latter case the secondary crushed material is fed to the 40 mm screen again. The material passing the 40 mm screen is the product. Changing the grading is possible by changing the screen size. The requirement on 28 mm sieve size for aggregate road base materials in Dubai is not met. In general the particle size distribution required in the Netherlands is more graded in the middle sizes, while the Dubai requirements show both relatively high coarse and fine contents. The performance of the Dutch graded material under Dubai circumstances for all three types of road base (granular subbase, aggregate road base and wet mix macadam) should be determined to establish the effect of the grading. Concrete granulate readily binds under Dutch circumstances, although the grading does not meet the Dubai requirements for aggregate road base material.

2.13.2 Maximum dry density (modified Proctor)

The density of 1870 kg/m3 determined does not meet the density of 2300 kg/m3 required for Dubai aggregate road base materials. This never is the case since massive concrete will hardly reach such densities. If a compacted lightweight granulate performs well as road base, there is no need for absolute densities to formulate. The contractors work should be controlled by determining the density relative to the maximum proctor density as determined in the laboratory.

2.13.3 CBR

The CBR is determined to conform to both Dutch and Dubai Standards. In both cases the material performs very well.

2.13.4 Organic impurities

If no cement is used as binder, the organic impurities are of no significance. Only visible organic mater should be limited as determined in the mixture composition test.

2.13.5 Mechanical strength

The LA-value does not meet the required value of 30% at maximum, due to the porous and therefore weaker cement matrix in the granulate. The aggregate crushing value (ACV) according to BS812 part 110 for wet mix macadam of 25% is just not met. The LA-value has to be adjusted to values of 40 or even 50% at maximum and the aggregate crushing value has to be adjusted to values of about 30%. The requirements for the Dutch aggregate crushing value are well met, which ensures excellent performance.

2.13.6 Soundness

The soundness (boiling test) according to ASTM, shows excellent behavior of concrete granulate. In the Netherlands no requirements are formulated for road base materials although the climate is relatively harsh, with wet and cold winters. The required soundness is questionable, since the climate in Dubai has no need for durability of the granulate.

2.13.7 Plasticity

In crushed concrete, the fines content is so low, that this material is not plastic. On recycled aggregate, no requirements should be stated for plasticity or liquid limit.

2.13.8 Linear shrinkage

Due to the low fines content the linear shrinkage will be negligible.

2.13.9 Chemical properties

Chloride or sulphate content does not affect the civil engineering properties of the material.

2.13.10 Particle shape

The flakiness and elongation indices are well met; therefore the requirements do not have to be adjusted for recycled material.

2.13.11 Mixture composition

The material does not (completely) meet the Dutch requirements for concrete granulate. The amount of masonry exceeds the limit by just 1.5%. In Dubai, requirements should be formulated to limit the amounts of by-constituents and impurities.

Tables 2.11, 2.12, and 2.13 shows the requirements for granulate for road bases.

Table 2.11. Requirements for Granulate for Road Bases (Granular Subbase Material) (reference No. 30)

No.	Requirement and method	Dubai limit virgin material	Proposed Dubai limit recycled material	Dutch limit recycled material
1	Los Angeles Abrasion ASTM C131/C535 Aggregate crushing value test 17 Standard RAW	≤ 30 %	≤ 45 %	- ≥ 0.65 per size fraction
2	Soundness $MgSO_4$ ASTM C88	≤ 12 %	≤ ??? %	-
3	Liquid limit BS 1377 part 2 test 4.5	≤ 35 %	-	-
4	Plasticity index BS 1377 part 2 test 5	≤ 6 %	-	-
5	Compaction test (modified Proctor) BS 1377 part 4 test 3.6	-	-	-
6	Soaked CBR at 95% mod. Proctor density BS 1377 part 4 test 7	≥ 30 %	-	-
	Dry CBR (0-days) at 100% normal Proctor BS 1377 part 4 test 7	-	≥ 50 %	≤ 50 %
	CBR increase (after 28 days of hardening at 20°c) BS 1377 part 4 test 7	-	≥ 125 %	≥ 125 %
7	Field density BS 1377 part 9 test 2.2	≥ 95 % MDD	≥ 98 % normal Proctor density 101 % mean	≥ 98 % normal Proctor density 101% mean
8	Linear shrinkage BS 1377 part 2 test 6.5	≤ 3 %	-	-
9	Sulphate content BS 812 part 118	≤ 0.5 %	-	-
10	Chloride content BS 812 part 117	≤ 1 %	-	-
11	Flakiness index BS 812 part 105.1	-	-	≤ 15 %
12	Elongation index BS 812 part 105.2	-	-	-
13	Sand equivalent ASTM D2419	-	-	-
14	Organic impurities BS 1377 part 3 test 3	-	-	-
15	Aggregate crushing value BS 812 part 110	-	≤ 30 %	-
	Aggregate crushing value Test 17 Standard RAW	-	-	≥ 0.65 per size fraction
16	Linear shrinkage BS 1377 part 2 test 6	-	-	-
17	Water absorption ASTM C127/C128	-	-	-

Table 2.12. Requirements for Granulate for Road Bases (Aggregate Road Base Material) (reference No. 30)

No.	Requirement and method	Dubai limit virgin material	Proposed Dubai limit recycled material	Dutch limit recycled material
1	Los Angeles Abrasion ASTM C131/C535 Aggregate crushing value test 17 Standard RAW	≤ 30 %	≤ 45 %	- ≥ 0.65 per size fraction
2	Soundness $MgSO_4$ ASTM C88	≤ 12 %	≤ ??? %	-
3	Liquid limit BS 1377 part 2 test 4.5	≤ 25 %	-	-
4	Plasticity index BS 1377 part 2 test 5	≤ 6 %	-	-
5	Compaction test (modified Proctor) BS 1377 part 4 test 3.6	≥ 2.3 Mg/m^3	-	-
6	Soaked CBR at 95% mod. Proctor density BS 1377 part 4 test 7	≥ 80 %	-	-
7	Dry CBR (0-days) at 100% normal Proctor BS 1377 part 4 test 7	-	≥ 50 %	≤ 50 %
	CBR increase (after 28 days of hardening at 20°c) BS 1377 part 4 test 7	-	≥ 125 %	≥ 125 %
8	Field density BS 1377 part 9 test 2.2	-	≥ 98 % normal Proctor density 101 % mean	≥ 98 % normal Proctor density 101% mean
9	Sulphate content BS 812 part 118	≤ 0.5 %	-	-
10	Chloride content BS 812 part 117	≤ 1 %	-	-
11	Flakiness index BS 812 part 105.1	≤ 35 %	-	≤ 15 %
12	Elongation index BS 812 part 105.2	≤ 35 %	-	-
13	Sand equivalent ASTM D2419	≥ 40 %	-	-
14	Organic impurities BS 1377 part 3 test 3	≤ 0.2 %	-	-
15	Aggregate crushing value BS 812 part 110	-	≤ 30 %	-
	Aggregate crushing value Test 17 Standard RAW	-	-	≥ 0.65 per size fraction
16	Linear shrinkage BS 1377 part 2 test 6	-	-	-
17	Water absorption ASTM C127/C128	-	-	-

Table 2.13. Requirements for Granulate for Road Bases (Wet-mix Macadam Road Base Material) (reference No. 30)

No.	Requirement and method	Dubai limit virgin material	Proposed Dubai limit recycled material	Dutch limit recycled material
1	Los Angeles Abrasion ASTM C131/C535 Aggregate crushing value test 17 Standard RAW	≤ 30 %	≤ 45 %	- ≥ 0.65 per size fraction
2	Soundness $MgSO_4$ ASTM C88	≤ 12 %	≤ ??? %	-
3	Liquid limit BS 1377 part 2 test 4.5	≤ 25 %	-	-
4	Plasticity index BS 1377 part 2 test 5	≤ 6 %	-	-
5	Compaction test (modified Proctor) BS 1377 part 4 test 3.6	-	-	-
6	Soaked CBR at 95% mod. Proctor density BS 1377 part 4 test 7	-	-	-
7	Dry CBR (0-days) at 100% normal Proctor BS 1377 part 4 test 7	-	≥ 50 %	≤ 50 %
	CBR increase (after 28 days of hardening at 20°c) BS 1377 part 4 test 7	-	≥ 125 %	≥ 125 %
8	Field density BS 1377 part 9 test 2.2	-	≥ 98 % normal Proctor density 101 % mean	≥ 98 % normal Proctor density 101% mean
9	Sulphate content BS 812 part 118	≤ 0.5 %	-	-
10	Chloride content BS 812 part 117	≤ 1 %	-	-
11	Flakiness index BS 812 part 105.1	≤ 30 %	-	≤ 15 %
12	Elongation index BS 812 part 105.2	≤ 30 %	-	-
13	Sand equivalent ASTM D2419	≥ 45 %	-	-
14	Organic impurities BS 1377 part 3 test 3	≤ 0.2 %	-	-
15	Aggregate crushing value BS 812 part 110	≤ 25 %	≤ 30 %	-
	Aggregate crushing value Test 17 Standard RAW	-	-	≥ 0.65 per size fraction
16	Linear shrinkage BS 1377 part 2 test 6	≤ 3 %	-	-
17	Water absorption ASTM C127/C128	≤ 2 %	-	-

CHAPTER THREE

Chapter Three

Methodology and Experimental Settings

In order to evaluate the performance of the RCA (Recycled Concrete Aggregate) as a component in the pavement structure an experimental model has been developed. In designing the model, the following items were considered:

- The model should as much as possible replicate the overall pavement structure in reality. That would entail utilizing a large-scale model to ensure the accuracy and the validity of the model results. The model should resemble the layered system of the pavement; namely, the thickness, the gradation of the material, and the order of the layers. Furthermore, the model dimensions should be set to allow the dissipation of stresses caused by the applied loads throughout the pavement structure. The model should be large enough to avoid the disturbances near the boundaries.
- The performance of the RCA material is best judged by measuring the strains associated with a specific stress. The lesser the strains, the lesser the probability that distresses will develop due to lateral displacements under the applied loads. In this research, the stress-strain relationships are obtained by measuring the

deflection caused by the various load levels. Measuring the deflection is not an easy task though. The fact that the RCA material is utilized as a loose material and that the expected deflection values are rather small (in the order of 0.1 mm) necessitates developing specific experimental settings to allow measuring the deflection accurately.

- Finally, in comparing the performance of the RCA material against the virgin natural material, it is essential to fix all experimental settings that might affect the results. For example, the gradation or size distribution of the two materials should be identical to alleviate the “grading” effect.

All the above items were taken into consideration in developing the experimental settings. This chapter is divided into five sections. Section 3.1 summarizes the design details of the mold devised for the experiments. Section 3.2 highlights some of the main properties of the materials used in the experiments. The details of the various experimental settings (definition of models) are summarized in Section 3.3. The compaction procedure utilized with all the models is briefly addressed in Section 3.4. Section 3.5 shows the details of the method used for deflection measurements.

3.1 The Mold Design

To measure the performance of the RCA material accurately, it was essential to devise the laboratory experiments in a way that resembles the real layered pavement structure. The experiment settings are designed to account for the typical layer’s thickness as well as the confined built through which the material acts. In reality, the material is confined within the overall pavement structure, which in turn is confided by the shoulder. The stresses dissipate throughout the pavement layers. The dissipation angle depends on the type of material to be used; the tougher the material, the higher the dissipation angle. A reinforced concrete box (mold) was designed and prepared for testing; the inner dimensions are 1 meter in length and width, and 0.8 meter in height. The dimensions were selected to allow free dissipation of stresses while minimizing the effect of mold walls (boundary conditions). Figure 3.1 shows all the details of the mold dimensions and structural details. The steel reinforcement distribution is shown in Figure 3.2. The mold empty weight is about 2,200 kg. This heavy weight will ensure the stability of the mold under the heavy applied loads to be used in the experiments.

3.2. Testing Materials

This section briefly reviews the specifications and the properties of the materials used in testing. The main material types used in these experiments are the subgrade materials, the subbase materials, the bituminous materials as well as the RCA materials. These materials are typically used for the majority of the road construction projects in the Emirate of Abu Dhabi.

3.2.1. Bituminous Mix Materials

Three main types of bituminous mix materials are widely used in the Emirate of Abu Dhabi for the construction of the base course, the binder course, and the wearing course.

(a)

(b)

(c)

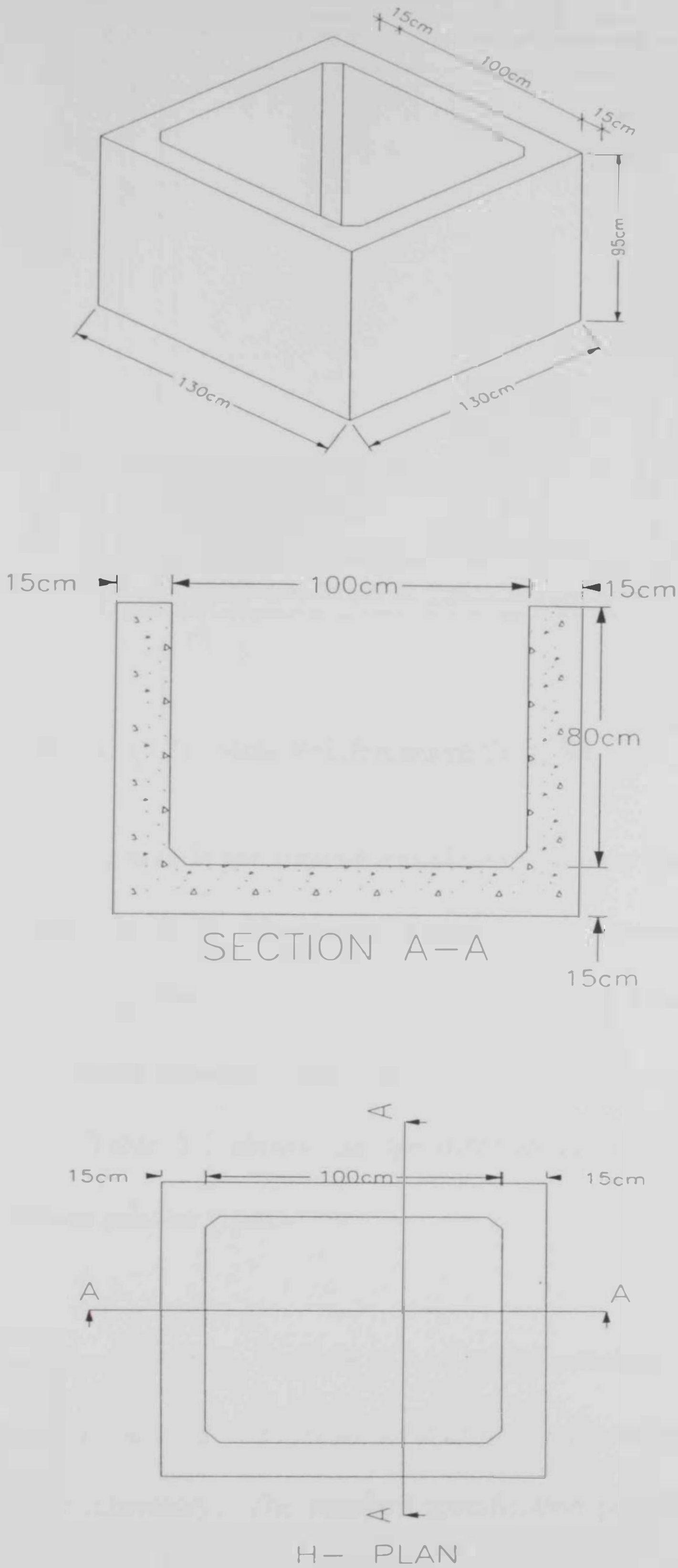


Figure (3.1): Mold Used in Testing: (a) Dimension Details, (b) Horizontal Plan for the Mold, (c) Cross Section of the Mold

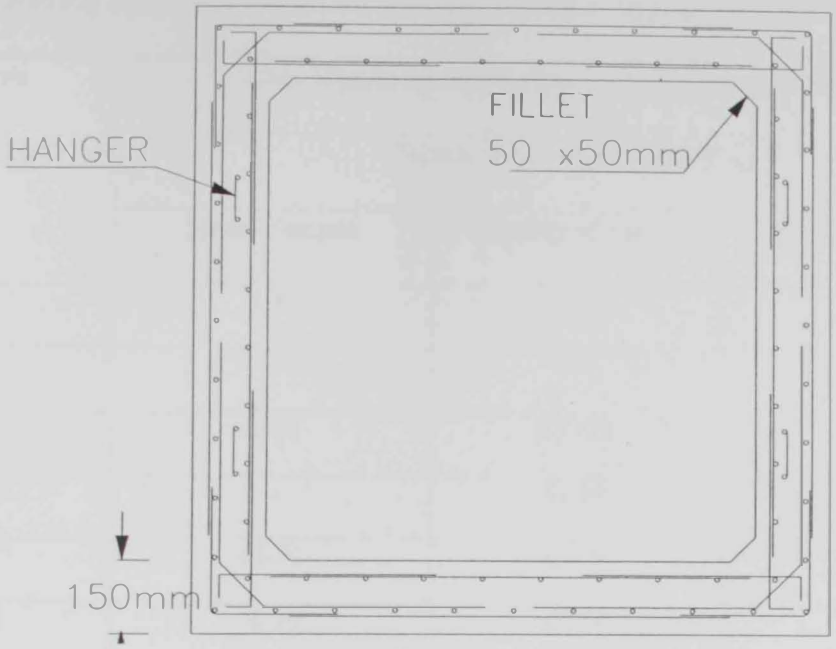


Figure (3.2): Mold Reinforcement Cross Section

The bituminous material source is the Bahrain Petroleum Company and can be classified as asphalt cement with grade 40-50. The mixture aggregates are processed lime aggregates extracted primarily from Al-Ain's wadi [31]. The Emirate of Abu-Dhabi adopts the material specifications of the American Association of State Highway and Transportation Officials (AASHTO). Table 3.1 shows the specification of the grading size of the aggregates for the various mixture types.

The construction specifications in the Emirate of Abu-Dhabi mandate that the bituminous mixtures be compacted in the field to a density level of not less than 98% of its maximum density obtained in the laboratory. The standard specification properties of bituminous mixtures used in this research are shown in Table 3.2.

Table 3.1 Grading Specifications of the Bituminous Mix Aggregates (Source: Ref. No. 31)

Sieve Size/ No.	Abu-Dhabi Specifications (% Passing Sieve Size)		
	Bituminous Mixture Type		
	Base Course	Binder Course	Wearing Course
1 ½ "	100	-	-
1 "	70-100	100	-
¾ "	62-92	80-100	100
½ "	--	63-85	80-100
3/8 "	45-75	57-77	65-85
# 4	30-55	40-60	46-63
# 10	20-40	25-45	30-50
# 20	15-30	18-33	22-38
# 40	10-20	13-25	15-27
# 80	6-15	8-17	10-20
# 100	2-8	5-10	5-12

Table 3.2 Properties of Bituminous Material Mixtures (Source: Ref. No. 31)

Mixture Properties	Bituminous Material Mixtures		
	Base Course	Binder Course	Wearing Course
Stability (Min), Kg "Marshall Testing"	900	1300	1500
Flow (mm) "Marshall Testing"	2-4	2-4	2-4
Stiffness (Minimum), Kg/mm	400	450	450
Air Void %	4-8	4-8	4-8
Voids in Mineral Agg. (Min), VMA%	13	13	14
% Voids Filled With Asphalt Cement	60-70	60-70	60-70
Loss of Stability: Marshall Test	Max. 25%	Max. 25%	Max. 25%

3.2.2. Subbase Materials

The material of the subbase should conform to the requirements specified for the class of subbase. There are three classes for the subbase materials used in Abu Dhabi: class A, B, and C. The sieve size requirements specified for class B (the one used in the tests of this research) are shown in Tables 3.3. The standard limitations of the aggregate properties are summarized in Table 3.4. These materials are a mix of Al-Ain's wadi gravels (40%) and borrow materials from Salamat borrow source (60%) [31]. Figure 3.3 shows the sieve analysis results for the actual subbase material used in the experiments.

Table 3.3 Sieve Analysis Requirements for the Class B Subbase Aggregates (Source: Ref. No. 31)

Sieve Size/Number	% Passing Sieve
2 "	100
1 ½ "	70-100
1 "	55-85
¾ "	50-80
3/8 "	40-70
# 4	30-60
# 10	20-50
# 40	10-30
# 200	5-15

Table 3.4 Class B Subbase Materials Properties (Source: Ref. No. 31)

Properties (Testing Method and Number)	Specification Requirement
Liquid limit (AASHTO T89)	25 maximum
Plasticity index (AASHTO T90)	4 maximum
Sand equivalent (AASHTO T176)	25 maximum
Loss of abrasion (AASHTO T96)	40 maximum
Maximum dry density (AASHTO T180)	2.0 gm/cc min.
C.B.R after 4 days soaking (B.S. 1377 part 4)	80 minimum

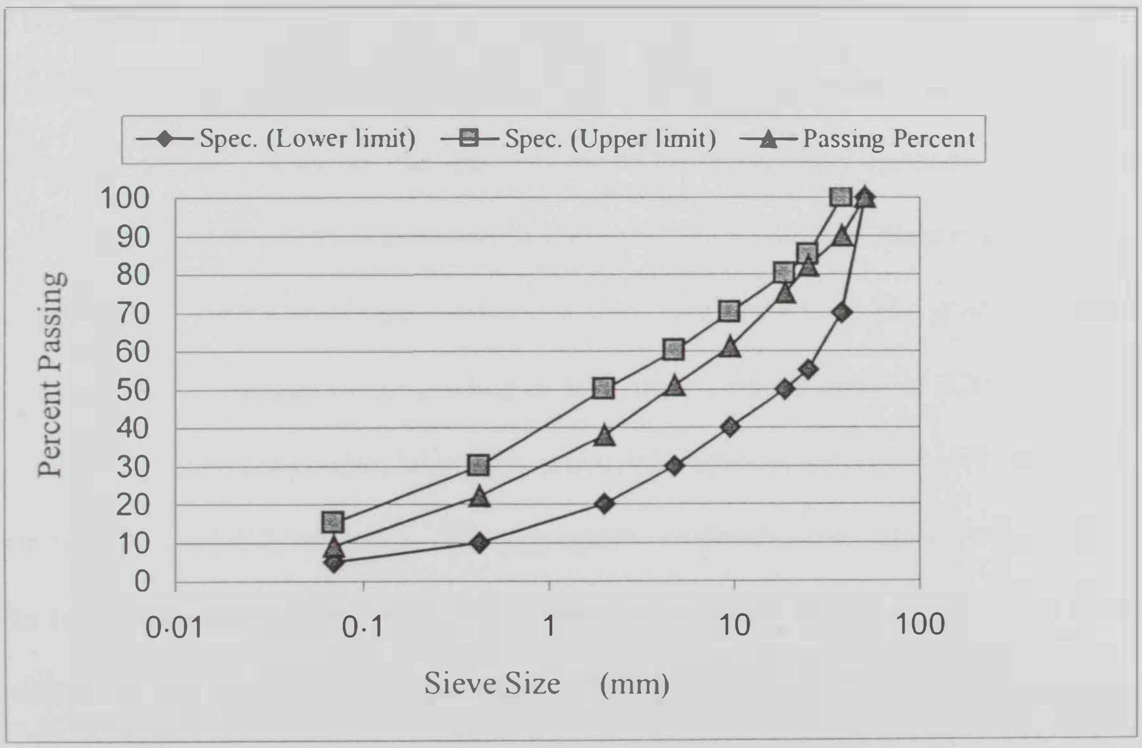


Figure (3.3): Sieve Analysis for the Actual Subbase Material Used in the Experiments

3.2.3. Subgrade Materials

The subgrade materials used in the tests were brought from the Salamat borrow source, and classified as (A-1-a) or (A-1-b) or (A-2-4). Table 3.5 illustrates the classification of soil and soil aggregate mixture. The CBR required for the subgrade material in the Emirate of Abu Dhabi is 30 % after 4 days soaking when compacted to 95% of its highest dry density obtained in the laboratory [31].

3.2.4. RCA Materials

The RCA materials were used as part of the subbase layer. The source of these materials is the testing cubes of concrete collected from different projects in Al Ain city. In this study, the concrete cubes were collected and crushed to the aggregate sizes of 3/8 inches maximum. Figure 3.4 shows the grading results of the crushed concrete cubes (RCA). The machine used in crushing is shown in Figure 3.5. The RCA subbase materials used in the experiments are a mix of virgin subbase material and the RCA. The grading of the mix was accurately set similar to the grading of the virgin subbase material (Class B grading). The mix is prepared by substituting the proportion passing sieve size 3/8 of the virgin material with the RCA materials. The aggregates coarser than the 3/8 inches size are kept from the virgin materials. That is, RCA materials replaced the finer part of the Class B gradation of the virgin aggregates. RCA material replaces 55 % by weight of the total weight of the mix, and the virgin material replaces only 45 % of the total weight of the mix. In addition, all the above materials were examined to be free from dirt, organic matter, shale or other deleterious matters.

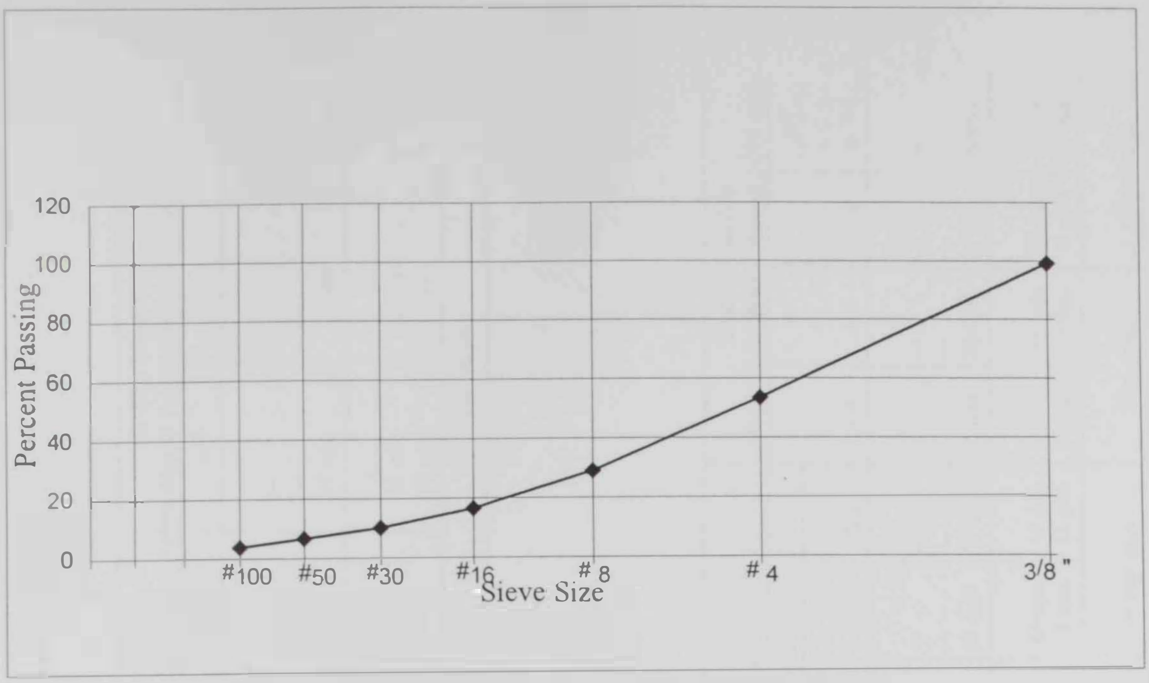
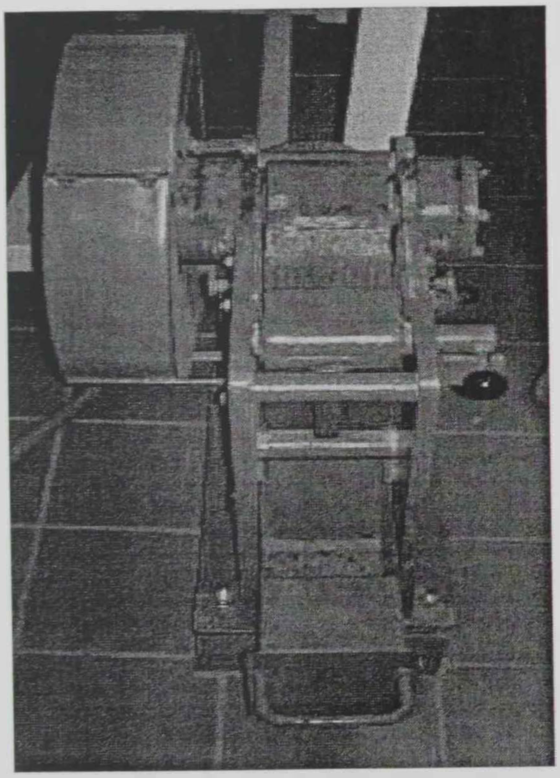
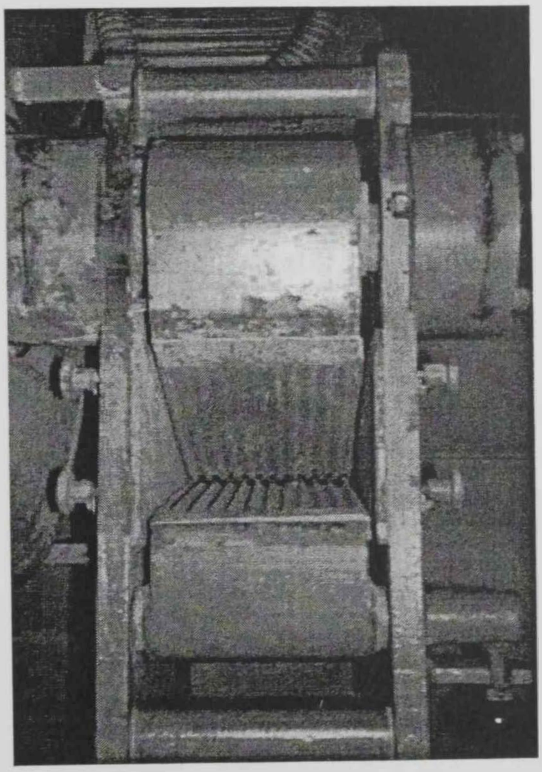


Figure (3.4): Sieve Analysis Results of the Crushed Concrete Cubes (RCA)



(a)



(b)

Figure (3.5): The Crusher Machine Used to Crush the Concrete Cubes:

(a) Front View (b) Top View

Table 3.5 Classification of Soil and Soil Aggregate Mixture (Source: Ref. No. 32)

General Classification	Granular Materials (35 Percent or Less Passing 0.075 mm)			Silt-Clay Materials (More than 35 Percent Passing 0.075 mm)			
Group Classification	A-1	A-3[a]	A-2	A-4	A-5	A-6	A-7
Sieve analysis, percent passing:							
2.00 mm (No. 10)	—	—	—	—	—	—	—
0.425 mm (No. 40)	50 max	51 min	—	—	—	—	—
0.075 mm (No. 200)	25 max	10 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing 0.425 mm (No. 40)							
Liquid limit	—	—		40 max	41 min	40 max	41 min
Plasticity index	6 max	N.P.		10 max	10 max	11 min	11 min
General rating as subgrade	Excellent to good			Fair to poor			

[a] The placing of A-3 before A-2 is necessary in the "left to right elimination process" and does not indicate superiority of A-3 over A-2.

General Classification	Granular Materials (35 Percent or Less Passing 0.075 mm)							Silt-Clay Materials (More than 35 Percent Passing 0.075 mm)			
	A-1			A-2							A-7
Group Classification	A-1-a	A-1-b	A-3	A-2-4	A-2-5	A-2-6	A-2-7	A-4	A-5	A-6	A-7-5, A-7-6
Sieve analysis, percent passing:											
2.00 mm (No. 10)	50 max	—	—	—	—	—	—	—	—	—	—
0.425 mm (No. 40)	30 max	50 max	51 min	—	—	—	—	—	—	—	—
0.075 mm (No. 200)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing 0.425 mm (No. 40)											
Liquid limit	—		—	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity index	6 max		N.P.	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min[a]
Usual types of significant constituent materials	Stone fragments, gravel and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General ratings as subgrade	Excellent to Good							Fair to poor			

[a] Plasticity index of A-7-5 subgroup is equal to or less than LL minus 30. Plasticity index of A-7-6 subgroup is greater than LL minus 30

3.3. Experimental Settings

Several experimental settings were devised to test the performance of the subbase mix (virgin plus RCA materials) against the performance of the only-virgin-materials subbase. The remaining of this section highlights the rationale and details of the various experimental settings.

3.3.1. Experimental Setting I (Initial Trial Test)

The objective of the trial test was to check the validity of the results of the model, as well as to check the deficiencies in the logistics of experimentation. This test was extremely helpful in learning several aspects of the experiments' logistics. In addition, it was heavily utilized to find (and examine) various solutions for the problems faced. The accuracy of the deflection measurements was to be assured throughout this setting. In general, this experimental setting was intended to assure that all the experiment's elements (such as the load cell machine, the dial gauges or the deflection bars) are functioning properly. This model setting was repeatedly altered to account for the identified testing problems. Figure 3.6 shows the cross-section of the mold with the layer thickness utilized in this trial test and shows also the gauges location for this test. The model constitutes three layers (all of the same source) of the subgrade materials. The deflection gauges were installed exactly at the interfaces of the layers at various radial distances from the center of the load. The idea is to be able to characterize the overall deflection basins at various depth, radial distance, and load combinations.

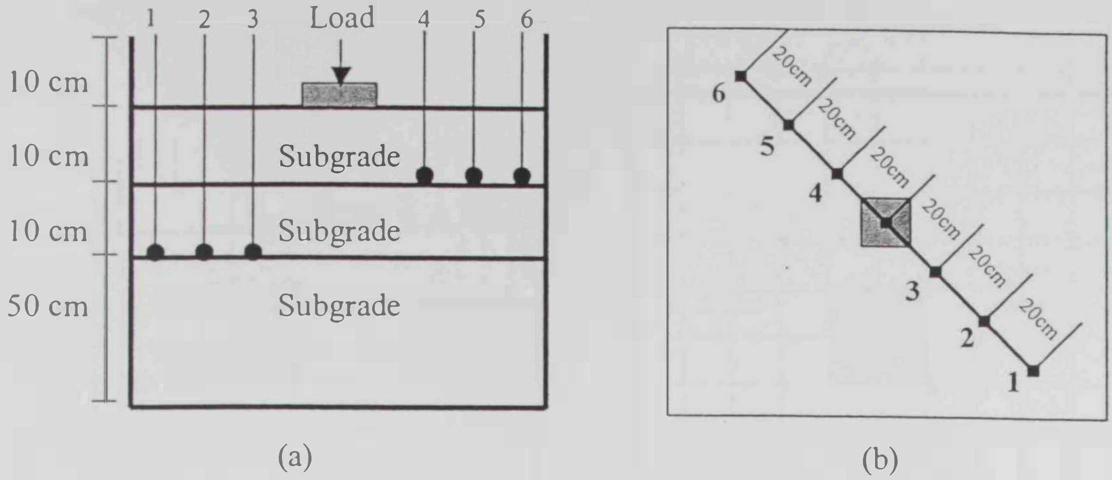


Figure (3.6): Model Description- Experimental Setting I: (a) Side View for the Gauges Location and the Layer Thicknesses, (b) Top View of the Gauges Location

3.3.2. Experimental Setting II

This experimental details and settings were initially set to replicate a typical pavement cross section. The model constitutes three layers: an asphalt concrete binder course of 10 centimeters, a subbase course of 10 centimeters of virgin class B materials, and 40 centimeters of the subgrade materials (four layers each of 10 centimeters). The point load to apply to this model ranges from 0 to 100 KN. A total of 18 points within the pavement structure were selected for deflection measurement. The points were selected to cover all the layer interfaces as well as various radial distances. The cross section of the mold and the layers' thickness are shown in Figure 3.7-a. The locations of the deflection gauges are shown in Figure 3.7-b.

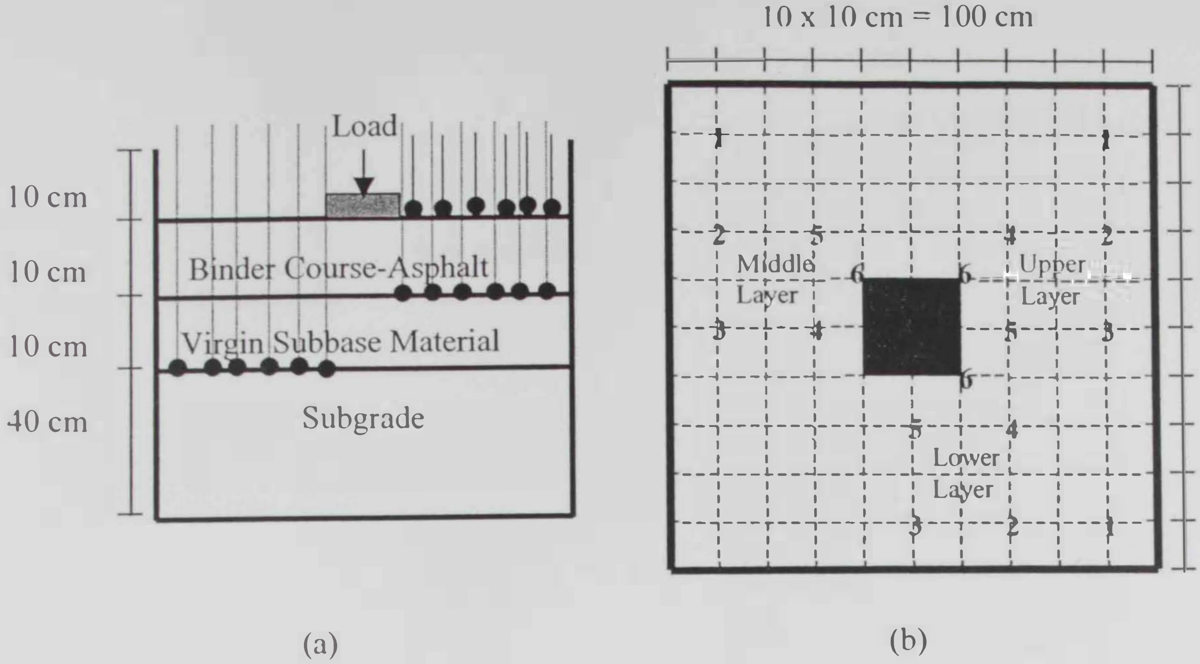


Figure (3.7): Model Description- Experimental Setting II: (a) Side View for the Layer Thicknesses and Material Types, (b) Top View of the Gauges Location

3.3.3. Experimental Setting III

This is the control sample, which was built up after considering the results of the two previous experiments. The model constitutes of two layers with two types of materials. A virgin subbase material of 20 centimeters compacted in two layers each at 10 centimeters, and 40 centimeters of subgrade material were compacted in 3 layers (20 cm + 10 cm + 10 cm). These are the same subbase materials used in most of the road construction of Abu Dhabi roads. The applied point load of this model ranges from 0 to 100 KN. A total of 18 points within the pavement structure were selected for deflection measurement. The points were selected to cover all the layer interfaces as well as various radial distances. The cross section of the mold and the layers' thickness are shown in Figure 3.8-a. The locations of the deflection gauges are shown in Figure 3.8-b.

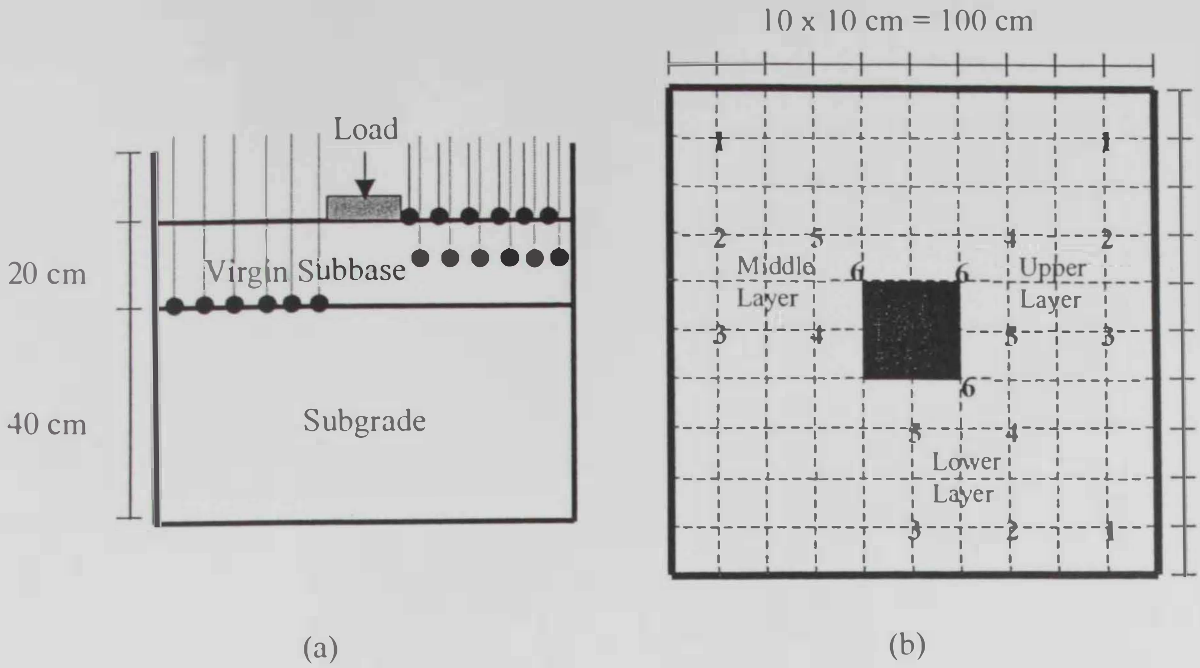


Figure (3.8): Model Description- Experimental Setting III: (a) Side View for the Layer Thicknesses and Material Types, (b) Top view of the Gauges Location

3.3.4. Experimental Setting IV

This experimental setting is aimed at studying the effects of using RCA materials. Through comparative analysis of the results of setting III and IV, the effects of the RCA materials can be concluded. The experimental setting is similar to experimental setting III. The model constitutes two layers with two types of materials. A RCA subbase materials of 20 centimeters compacted in two layers each at 10 centimeters, and 40 centimeters of subgrade material were compacted in 3 layers (20 cm + 10 cm + 10 cm). The only difference (compared to experiment III) was in replacing the virgin subbase material with the RCA subbase material. The cross section of the mold and the layers' thickness are shown in Figure 3.9-a. The locations of the deflection gauges are shown in Figure 3.9-b.

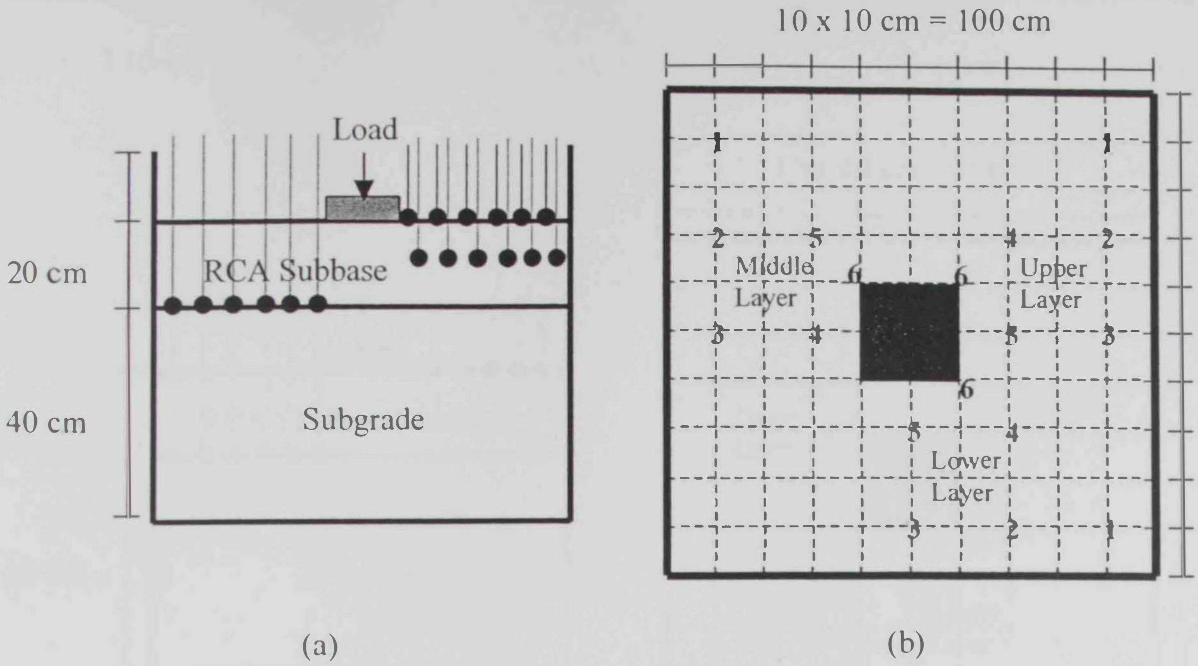


Figure (3.9): Model Description- Experimental Setting IV: (a) Side View for the Layer Thicknesses and Material Types, (b) Top View of the Gauges Location

3.3.5. Experimental Setting V

This experimental setting is aimed at studying the effect of the RCA laying/applying load time period. Through comparative analysis of the results of this setting and setting VI, the effect of the RCA laying/applying load can be concluded. The experimental setting is similar to experimental setting IV. The model constitutes two layers with two types of materials. A RCA subbase material of 10 centimeters compacted as one layer, and 40 centimeters of subgrade material were compacted in three layers at (20 cm + 10 cm + 10 cm). The only difference is the reduction of the depth layer of the RCA subbase materials from 20 centimeter to 10 centimeter. In this experiment, the time period between laying the pavement layers and applying of load was very short; the test was carried out only one day after laying the pavement layers. The cross-section of the mold and the layers' thickness are shown in Figure 3.10-a. The locations of the deflection gauges are shown in Figure 3.10-b.

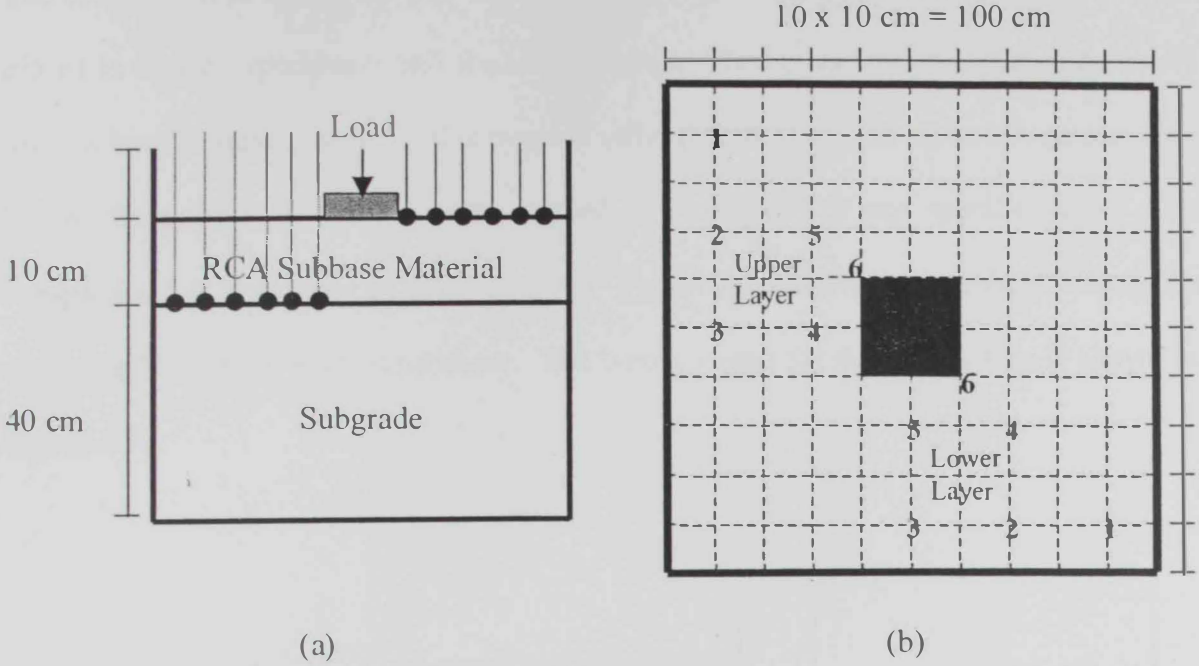


Figure (3.10): Model Description- Experimental Setting V: (a) Side View for the Layer Thicknesses and Material Types, (b) Top View of the Gauges Location

3.3.6. Experimental Setting VI

This experimental setting is aimed at studying the effect of the RCA laying/applying load time period and the effect of RCA layer thickness. Through comparative analysis of the results of this setting and setting V, the effect of the RCA laying/applying load can be concluded. Through comparative analysis of the results of this setting and setting IV the effect of the RCA layer thickness can be concluded. All experimental details and settings for this experiment are exactly the same as experimental setting V (See Figure 3.10). The only difference (compared to experiment V) was in extending the time period (between laying the pavement layers and applying the load) to about three weeks instead of one day as was done in experiment V.

3.4. Layer's Compaction

The compaction of the layers was kept identical (to alleviate the effect of the compaction effort) in all the experiments and for all the layers. The layers were compacted manually using a long hammer, made for this purpose only. It weighs around seven kilograms. Ten blows (from the same height) were applied to each point of any specific layer. The compaction has been done in several layers. Figure 3.11 shows the interfaces among the compacted layers for each experiment. The hammer used for the compaction is shown in Figure 3.12.

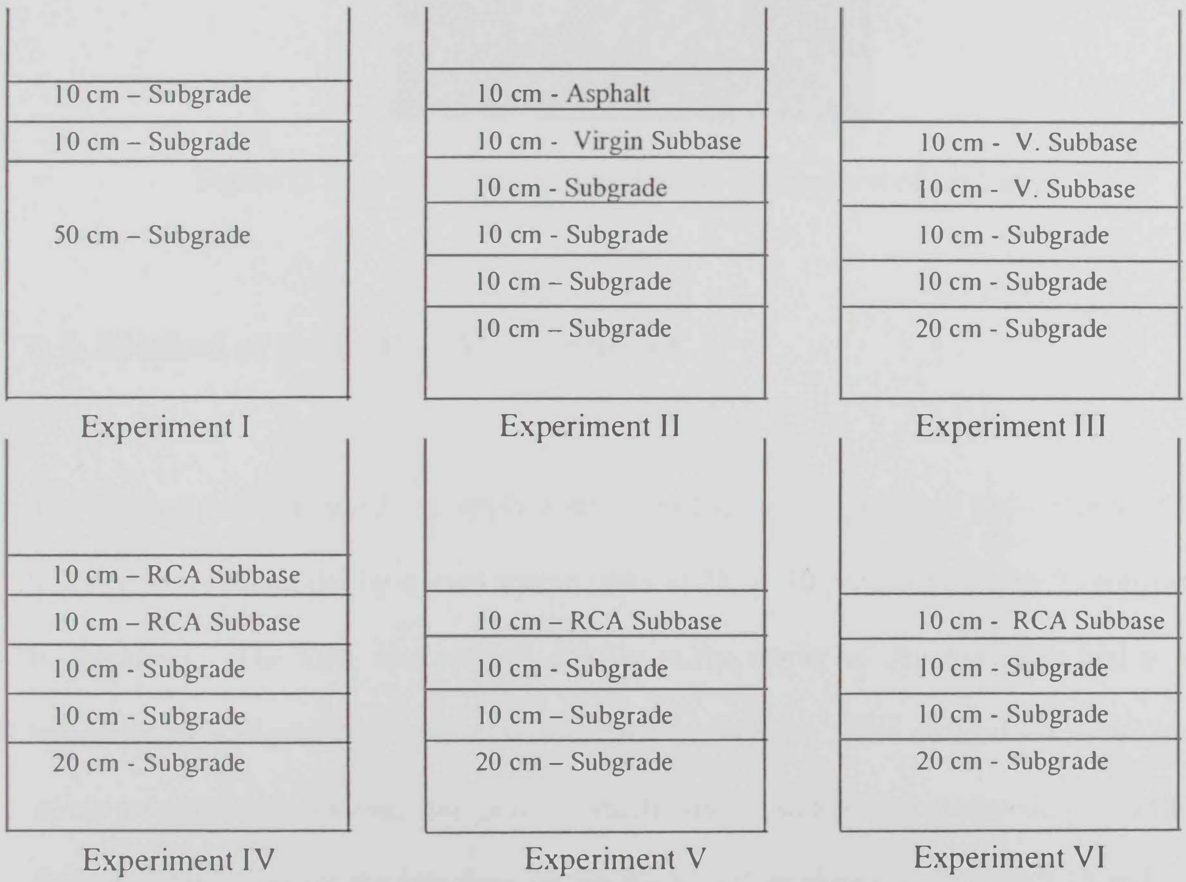


Figure (3.11): Compaction Location of the Pavement Layers for each Experiment

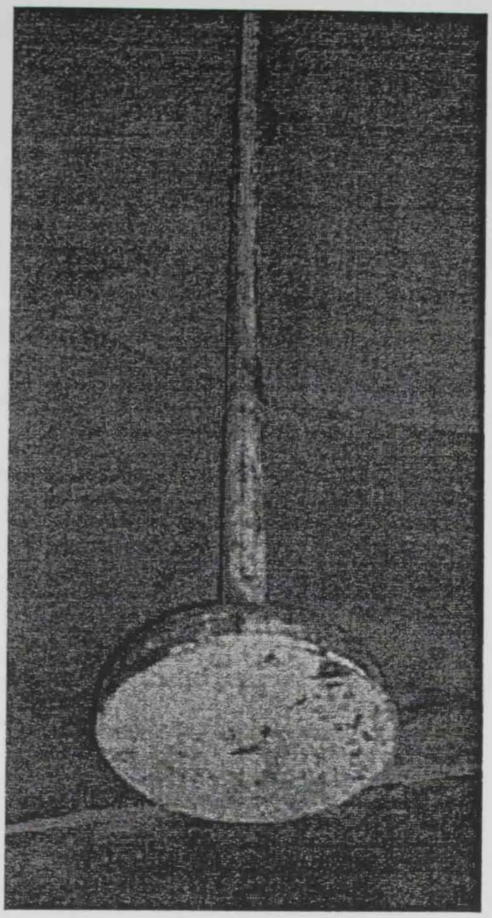


Figure (3.12): The Hammer Used in the Compaction of the Layers

3.5. Method of Deflection Measurement

The loading machine used can apply a static load up to one hundred KN. The load was transferred to the model by a steel square plate of 20 by 20 centimeters with 2 centimeters in thickness. The load was applied exactly at the center of the top layer and it was measured by a digital unit to display the exact load values. The deflections in the lower layers were measured using dial gauges, which were in touch with steel rods that settle at the top of the layers (at the interface among the layers) as shown in Figures 3.13 and 3.15-a. These rods were installed in plastic pipes to avoid the friction of the rod surface with the material in the layers and to keep the rods in exact vertical positions. A system was built to allow the free movement of the dial gauges in all directions (up and down, left and right, forward and backward). Up to eighteen dial gauges were used in some of the experiments and that made the process of fixing the gauges very difficult. Each group of pipes (residing on the same layer) was fixed in place using a ring metal bar to ensure the stability of rods while carrying out the test. Figure 3.13 shows the overall system of the structure elements. The rod dimensions are shown in Figure 3.14. The locations of the gauges of each experiment were shown previously. Figure 3.15 shows a photo of the concrete mold with the load cell and the dial gauges.

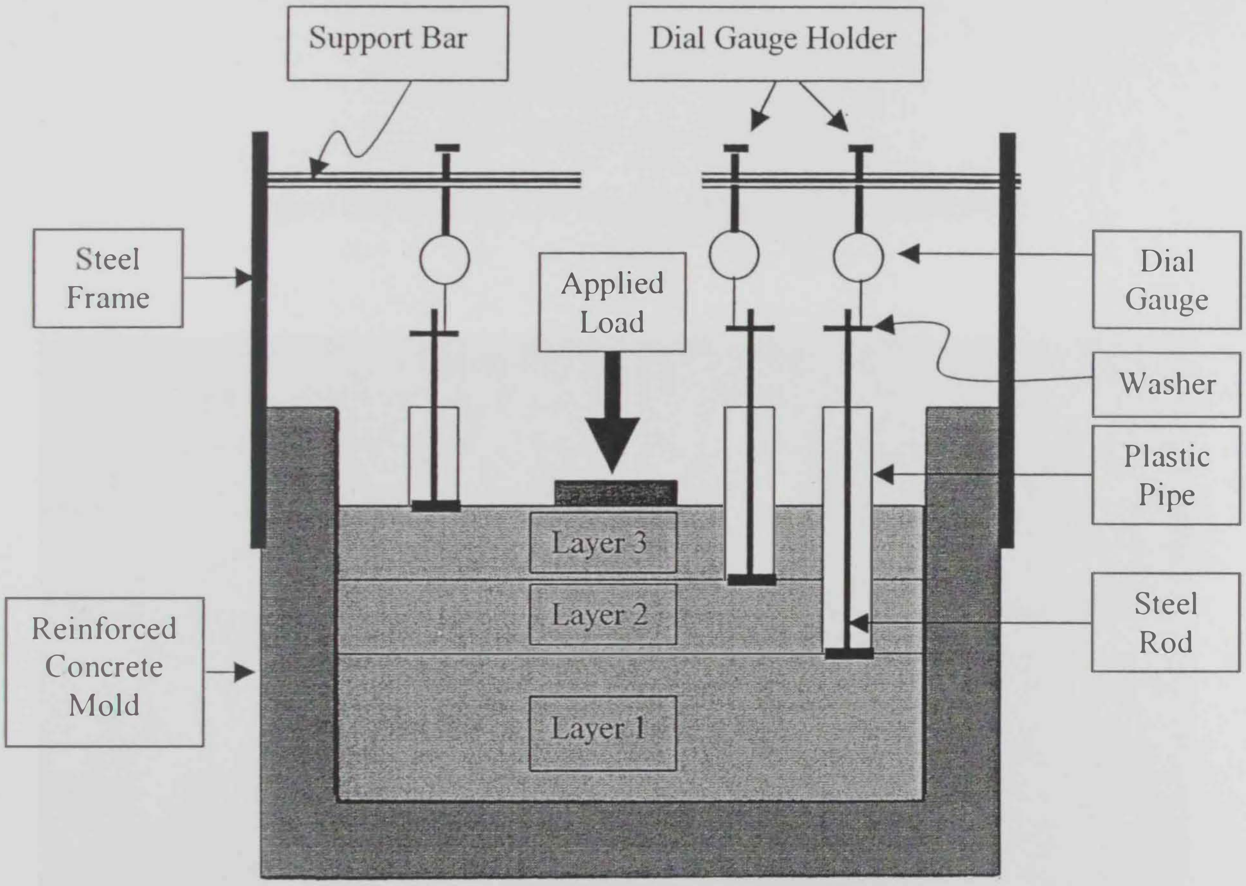


Figure (3.13): Overall System of the Structural Elements

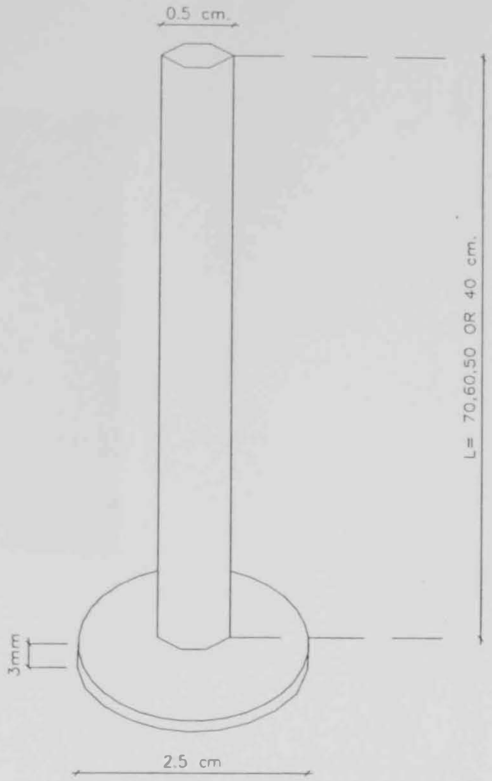
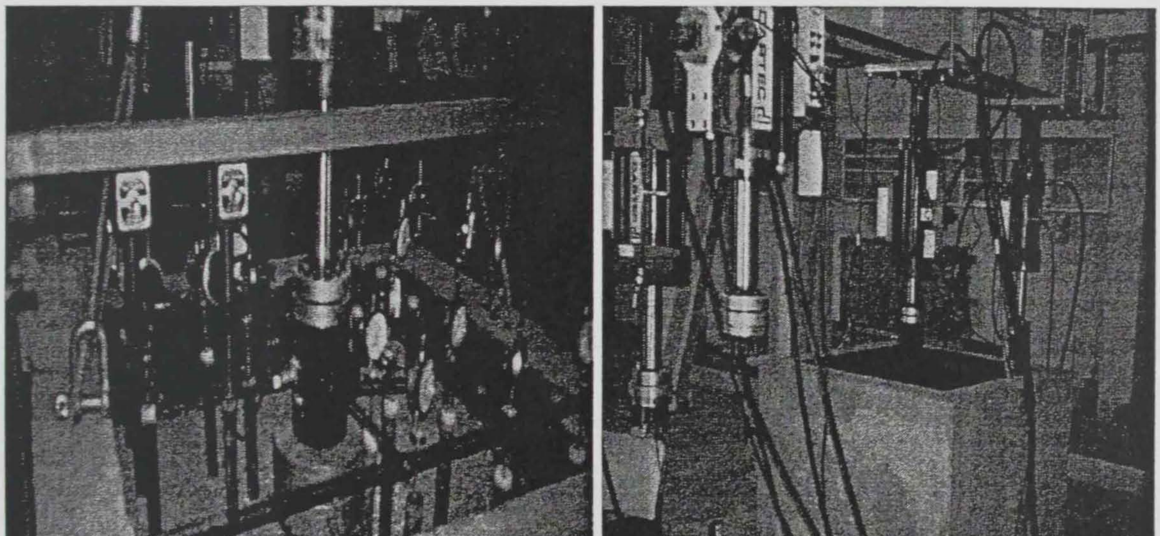


Figure (3.14): Steel Rod Used in Measuring the Deflections



(a) (b)

Figure (3.15): The Concrete Mold with: (a) Gauges Set, (b) Load Cell

CHAPTER FOUR

Chapter Four

Results and Analysis

4.1 Introduction

As previously indicated in Chapter one, the primary objective of this study is the assessment of the performance of the RCA subbase material under the application of load. The results of the experimental program are being presented and discussed in this Chapter. The conclusions of the RCA performance can be made by studying the basin of deflection under the various loading levels. This chapter is divided into five sections. Section 4.2 summarizes all the experimental results in tabulated forms. Section 4.3 focuses on the overall deflection results of experiments III, and IV. The effect of using different types of materials is discussed in Section 4.4. The effect of the layer thicknesses of RCA material is addressed in Section 4.5. Section 4.6 discusses the effect of the testing age which; is the time difference between laying down the RCA layers after compaction and the time the load is applied.

4.2 Experimental Results

A total of six experiments were performed. The first one was the pilot experiment to check the adequacy of the model, as well as to check the deficiencies in the logistics of experimentation. The results obtained from all the experiments were seen to be consistent with the exception of experiment II. The remainder of this section tabulates the findings of all the experiments.

4.2.1 Experiment I

Table 4.1 shows the results of the pilot experiment using only virgin subgrade materials. Figure 4.1 shows the points at which the deflection was measured. The results of deflection measurements are given in millimeters. The negative values indicate downward deflection. The closer the point to the center of the applied load, the higher the values of deflection. It is worth noting that the points closer to the mold boundaries exhibited positive (upward) deflection. This could be attributed to the downward movement of the material under the effect of the applied load near the center. The downward movement near the center pushes aside and upward the loose mold materials near the boundaries. This affects the results in positive (upward) movement; the higher the load, the higher the positive deflection values. In general, the positive upward deflection is mostly experienced at the upper layers and near the boundaries (away from the area of load influence). For example, points 3 and 4 are at the same horizontal distance from the mold center, point 3 shows negative values and point 4 shows positive values, the reason for such case will be discussed in Section 4.4. The dash (-) values in Table 4.1 indicates a malfunction in the dial gauge, and hence no reading. The word "failure" indicates the punching of the pavement surface layer, and hence no further measurements could be taken. In general, the results of this experiment could be utilized as a benchmark to measure the effect of material quality and/or thickness in any other model. The results of this experiment shows

Table 4.1. Results of Experiment I (Pilot Experiment)

Distance from load center	Point Number	Deflection (mm)							
		10 KN	20 KN	30 KN	40 KN	50 KN	60 KN	70 KN	> 70 KN*
60 cm	1	0	0	+0.005	+0.01	+0.01	+0.025	+0.04	Failure
40 cm	2	-0.03	-0.035	-0.04	-0.052	-0.06	-	-	Failure
20 cm	3	-0.145	-0.275	-0.395	-0.565	-1.335	-1.505	-2.895	Failure
20 cm	4	+0.17	+0.415	+0.535	+0.675	+1.032	+1.187	+1.732	Failure
40 cm	5	0	+0.035	+0.04	+0.07	+0.05	+0.035	-0.02	Failure
60 cm	6	0	+0.09	+0.105	+0.105	+0.17	+0.18	-	Failure

* At this level of loading, the applied load punched through the surface layer.

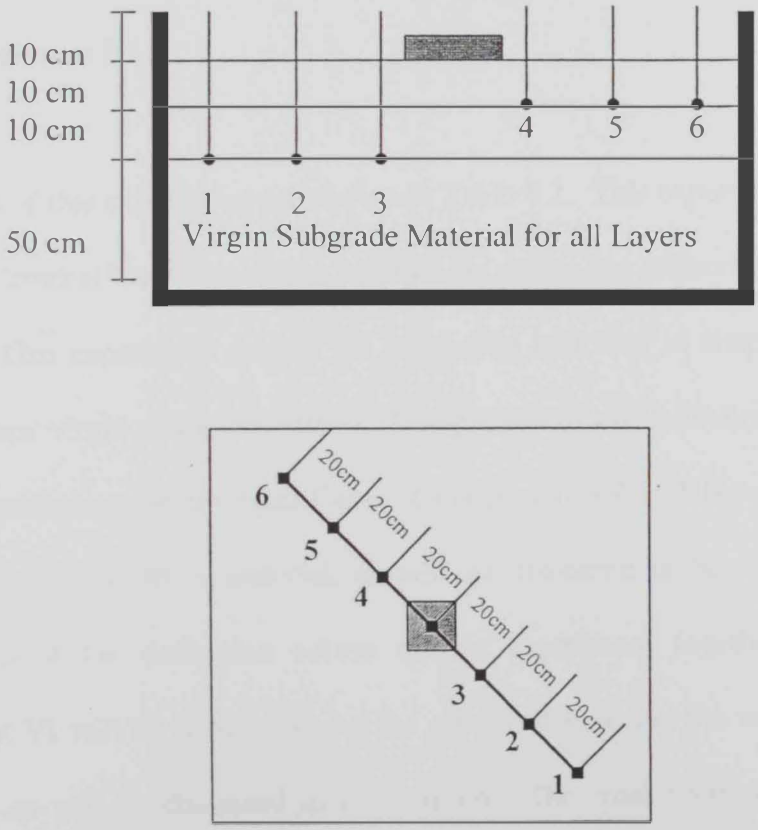


Figure (4.1): Deflection Locations for Experiment I (Pilot Experiment)

4.2.2 Experiment II

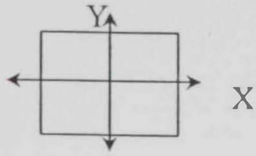
Experimental setting II was initially set to replicate a typical pavement cross-section. Applying a load of up to 100 KN did not result in any measurable affect on the pavement and zero deflection values were recorded. This could be attributed to the high modulus of elasticity of the surface layer. The highly stiff surface layer acts as a "slab" that distributes the load stresses equally underneath. In other words, the area of load influence becomes big enough to result in very small stress levels and hence very small deflection values that could not be recorded by the utilized deflection gauges. Given these results, it was decided to test the subbase materials without using the surface layer for all the remaining experiments.

4.2.3 Experiment III

The results of this experiment are shown in Table 4.2. This experiment is considered to be the "control" test that could be used to assess the effectiveness of the RCA material. This experiment setting (as previously indicated in chapter 3) constitutes 20-centimeter virgin subbase material. Comparison of the deflection values recorded in this experiment together with those of experiment IV will be used to assess the performance of the RCA material, as will be discussed in Section 4.3. Another comparison of the deflection values of this experiment together with those of experiment VI will be used to assess the effects of reducing the subbase RCA layer thickness, as will be discussed in Section 4.4. The cross section of the mold, the thickness of layers, and the location of the deflection gauges are shown in Figure 3.8 in Chapter 3.

Table 4.2. Results of Experiment III

Point	Dis. to load center	Point	Dis. to load center
1	56.56 cm	4	28.28 cm
2	44.72 cm	5	20 cm
3	40 cm	6	14.14 cm



Layer No. (1) Top of virgin subbase layer

Points	Point position		Deflection Values (mm) with Applied Load (KN)									
	X	Y	10	20	30	40	50	60	70	80	90	100
Point1	40	40	0	0	0	0	0	+0.03	+0.04	+0.07	+0.13	+0.17
Point2	20	40	0	0	0	0	0	+0.13	+0.18	+0.26	+0.39	+0.49
Point3*	0	40	-	-	-	-	-	-	-	-	-	-
Point4	20	20	0	0	0	0	0	0	0	+0.01	+0.35	+0.7
Point5	0	20	0	0	0	0	-0.02	-0.04	-0.19	-0.52	-0.84	-1.1
Point6*	10	10	-	-	-	-	-	-	-	-	-	-

Layer No. (2) Middle of virgin subbase layer

Points	Point position		Deflection Values (mm) with Applied Load (KN)									
	X	Y	10	20	30	40	50	60	70	80	90	100
Point1	40	40	0	0	+0.09	+0.14	+0.2	+0.32	+0.4	+0.47	+0.53	+0.62
Point2*	20	40	-	-	-	-	-	-	-	-	-	-
Point3	0	40	0	0	-0.18	-0.23	-0.23	-0.23	-0.48	-0.53	-0.86	-1.4
Point4	20	20	0	0	0	-0.18	-0.3	-0.48	-0.55	-0.78	-1.02	-1.8
Point5	0	20	0	0	-0.1	-0.5	-1.74	-1.91	-2.06	-2.09	-2.09	-2.09
Point6	10	10	0	-0.7	-1.02	-1.48	-1.84	-2.64	-3.65	-4.36	-5.28	-6.31

Layer No. (3) Top of subgrade layer

Points	Point position		Deflection Values (mm) with Applied Load (KN)									
	X	Y	10	20	30	40	50	60	70	80	90	100
Point1	40	40	0	0	0	0	0	0	0.016	+0.016	+0.102	+0.104
Point2	20	40	0	-0.2	-0.3	-0.31	-0.31	-0.31	-0.31	-0.31	-0.31	-0.31
Point3	0	40	0	+0.15	+0.31	+0.47	+0.6	+0.7	+0.89	+1.05	+1.32	+1.4
Point4*	20	20	-	-	-	-	-	-	-	-	-	-
Point5	0	20	0	0	0	-0.1	-0.4	-0.74	-1	-1.29	-2	-3.8
Point6	10	10	0	0	-0.25	-0.84	-1.59	-2.38	-3.16	-3.92	-4.64	-5.26

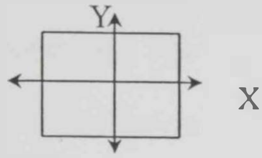
* No values were recorded due to gauge error.

4.2.4 Experiment IV

This represents the experiment with the 20-centimeter subbase RCA material. Table 4.3 shows the results of this experiment. Comparison of the deflection values of this experiment together with those of experiment III will be used to assess the performance of the RCA material, as will be discussed in Section 4.3. The cross section of the mold, the layers' thickness, and the location of the deflection gauges are shown in Figure 3.9.

Table 4.3. Results of Experiment IV

Point	Dis. to load center	Point	Dis. to load center
1	56.56 cm	4	28.28 cm
2	44.72 cm	5	20 cm
3	40 cm	6	14.14 cm



Layer No. (1) Top of RCA subbase layer

Points	Point position		Deflection Values (mm) with Applied Load (KN)									
	X	Y	10	20	30	40	50	60	70	80	90	100
Point1	40	40	0	0	0	0	0	0	0	0	0	0
Point2	20	40	0	0	0	0	0	0	0	0	0	0
Point3	0	40	0	0	0	0	0	0	0	0	0	0
Point4	20	20	0	0	0	0	0	0	0	0	0	0
Point5	0	20	0	0	0	0	0	0	0	0	0	0
Point6	10	10	0	0	0	0	0	0	0	0	-0.01	-0.03

Layer No. (2) Middle of RCA subbase layer

Points	Point position		Deflection Values (mm) with Applied Load (KN)									
	X	Y	10	20	30	40	50	60	70	80	90	100
Point1	40	40	0	0	0	0	0	0	0	0	0	0
Point2	20	40	0	0	0	0	0	0	0	0	0	0
Point3	0	40	0	0	0	0	0	0	0	0	+0.06	+0.1
Point4	20	20	0	0	0	0	0	0	0	0	0	0
Point5	0	20	-0.1	-0.15	-0.26	-0.38	-0.5	-0.6	-0.7	-0.8	-0.9	-0.95
Point6	10	10	0	-0.37	-0.57	-0.87	-1.19	-1.57	-1.82	-2.17	-2.65	-2.99

Layer No. (3) Top of subgrade layer

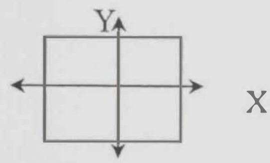
Points	Point position		Deflection Values (mm) with Applied Load (KN)									
	X	Y	10	20	30	40	50	60	70	80	90	100
Point1	40	40	0	0	0	0	0	0	0	0	0	0
Point2	20	40	0	0	0	0	0	0	0	0	0	-0.12
Point3	0	40	0	0	0	0	0	0	0	0	0	0
Point4	20	20	0	0	0	0	0	0	0	0	0	0
Point5	0	20	0	0	-0.05	-0.24	-0.4	-0.55	-0.75	-0.93	-1.15	-1.34
Point6	10	10	0	0	-0.3	-0.57	-0.75	-1	-1.27	-1.57	-1.9	-2.24

4.2.5 Experiment V

This is the experiment with the 10-centimeter subbase RCA material. In this experiment the period between laying the pavement layers and applying the load was one day only. Comparison of the deflection values of this experiment together with those of experiment VI will be used to assess the effects of RCA curing time, as will be discussed in Section 4.5. Table 4.4 shows the results of this experiment. The cross-section of the mold, the layers thickness, and the location of the deflection gauges are shown in Figure 3.10.

Table 4.4. Results of Experiment V

Point	Dis. to load center	Point	Dis. to load center
1	56.56 cm	4	28.28 cm
2	44.72 cm	5	20 cm
3	40 cm	6	14.14 cm



Layer No. (1) Top of RCA subbase layer

Points	Point position		Deflection Values (mm) with Applied Load (KN)									
	X	Y	10	20	30	40	50	60	70 +	80	90	100
Point1	40	40	0	+0.15	+0.32	+0.38	+0.7	+0.7	Failure			
Point2	20	40	0	+0.4	+0.95	+1.35	+1.6	+2.6	Failure			
Point3	0	40	0	+0.24	+0.28	+0.28	+0.28	+0.28	Failure			
Point4	20	20	0	+0.03	+0.7	+1.25	+4.4	+7.5	Failure			
Point5	0	20	0	0	0	0	0	+4.1	Failure			
Point6	10	10	0	-1.31	-2.32	-3.15	-4.35	-8.54	Failure			

Layer No. (2) Top of subgrade layer

Points	Point position		Deflection Values (mm) with Applied Load (KN)									
	X	Y	10	20	30	40	50	60	70	80 +	90	100
Point1	40	40	0	0	0	+0.02	+0.06	+0.06	+0.07	Failure		
Point2	20	40	0	0	0	+0.11	+0.14	+0.17	+0.17	Failure		
Point3	0	40	0	+0.1	+0.2	+0.88	+0.89	+0.89	+0.89	Failure		
Point4*	20	20	-	-	-	-	-	-	-	Failure		
Point5	0	20	0	0	0	+0.2	+0.2	+0.47	+0.47	Failure		
Point6	10	10	0	-0.31	-0.81	-1.66	-2.25	-2.45	-3.09	Failure		

* No values were recorded due to gauge error.

+ At this level of loading, the applied load punched through the surface layer.

4.2.6 Experiment VI

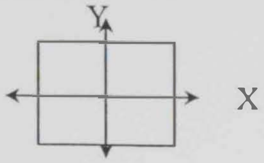
This is the experiment with the 10-centimeter subbase RCA material. In this experiment the period between laying the pavement layers and applying the load was three weeks. Comparison of the deflection values of this experiment together with those of experiment III will be used to assess the effects of reducing the subbase RCA layer thickness, as will be discussed in Section 4.4. Another comparison of the deflection values of this experiment together with those of experiment V will be used to assess the effect of RCA curing time, as will be discussed in Section 4.5. Table 4.5 shows the results of this experiment. The cross-section of the mold, the layers' thickness, and the location of the deflection gauges are shown in Figure 3.10.

4.3 Overview of Deflection Results

Figure 4.2 shows the deformed profiles of the surface of the two layers using plain virgin material. As expected, higher loads resulted in higher deflection values. The relationship, however, between load and deformations did not follow linear actions. At the surface layer (see Figure 4.2-a), the deformation started to appear after a load of 50 KN. The profile of the surface layer showed a downward deformation for point 5. Deflection for point 6 was not recorded due to gauges error. It`s expected that this point to exhibit downward deformation as well. Beyond point 5, upward lift was recorded. At the subgrade layer (see Figure 4.2-b), the deformation started to appear at a load of 20 KN. The profile of the subgrade layer showed also a downward deformation mainly for points 5, and 6; which are the nearest points to the loading center. Points 1 and 3, which are near to the edges, showed upward deformation. The reason for such action is attributed to the effect of material displacement from the center to the edges.

Table 4.5. Results of Experiment VI

Point	Dis. to load center	Point	Dis. to load center
1	56.56 cm	4	28.28 cm
2	44.72 cm	5	20 cm
3	40 cm	6	14.14 cm



Layer No. (1) Top of RCA subbase layer

Points	Point position		Deflection Values (mm) with Applied Load (KN)									
	X	Y	10	20	30	40	50	60	70	80	90	100
Point1	40	40	0	0	0	0	0	0	0	-0.07	-0.1	-0.17
Point2*	20	40	-	-	-	-	-	-	-	-	-	-
Point3	0	40	0	+0.05	+0.18	+0.31	+0.47	+0.67	+0.96	+1.27	+1.47	+1.66
Point4	20	20	0	0	0	0	0	0	0	0	-0.14	-0.14
Point5	0	20	0	0	+0.07	+0.23	+0.37	+0.39	+0.39	+0.4	+0.4	+0.4
Point6	10	10	0	0	0	0	-0.03	-0.04	-0.05	-0.05	-0.05	-0.05

Layer No. (2) Top of subgrade layer

Points	Point position		Deflection Values (mm) with Applied Load (KN)									
	X	Y	10	20	30	40	50	60	70	80	90	100
Point1*	40	40	-	-	-	-	-	-	-	-	-	-
Point2	20	40	0	+0.19	+0.31	+0.31	+0.46	+0.47	+0.62	+0.64	+0.67	+0.67
Point3	0	40	0	+0.13	+0.22	+0.26	+0.36	+0.44	+0.54	+0.66	+0.71	+0.84
Point4	20	20	+0.29	+0.6	+0.92	+1	+1.32	+1.46	+1.84	+2.17	+2.57	+2.71
Point5	0	20	0	0	0	0	0	0	0	0	0	+0.27
Point6	10	10	0	0	-0.02	-0.43	-0.7	-1.14	-1.43	-1.95	-2.53	-3.5

* No values were recorded due to gauge error.

Figure 4.3 shows the deformed profiles of the surface of the two layers using RCA subbase material. As expected, higher loads resulted in higher deflection values. The relationship, however, between load and deformations did not follow linear actions. At the surface layer (see Figure 4.3-a), the deformation started to appear at a load of 90 KN and only at the nearest point to the loading center (point 6). The profile of the surface layer showed a downward deformation for point 6 only and no deformation was recorded beyond this point. At the subgrade layer (see Figure 4.3-b), the deformation started to appear with a load of 30 KN. The profile of the subgrade layer showed a downward deformation for point 5 and 6 mainly, although point 2 shows a slight deflection at maximum load only. No deformation was recorded beyond this distance. The reason for such action is attributed to the effect of material type which; will be discussed in Section 4.3.

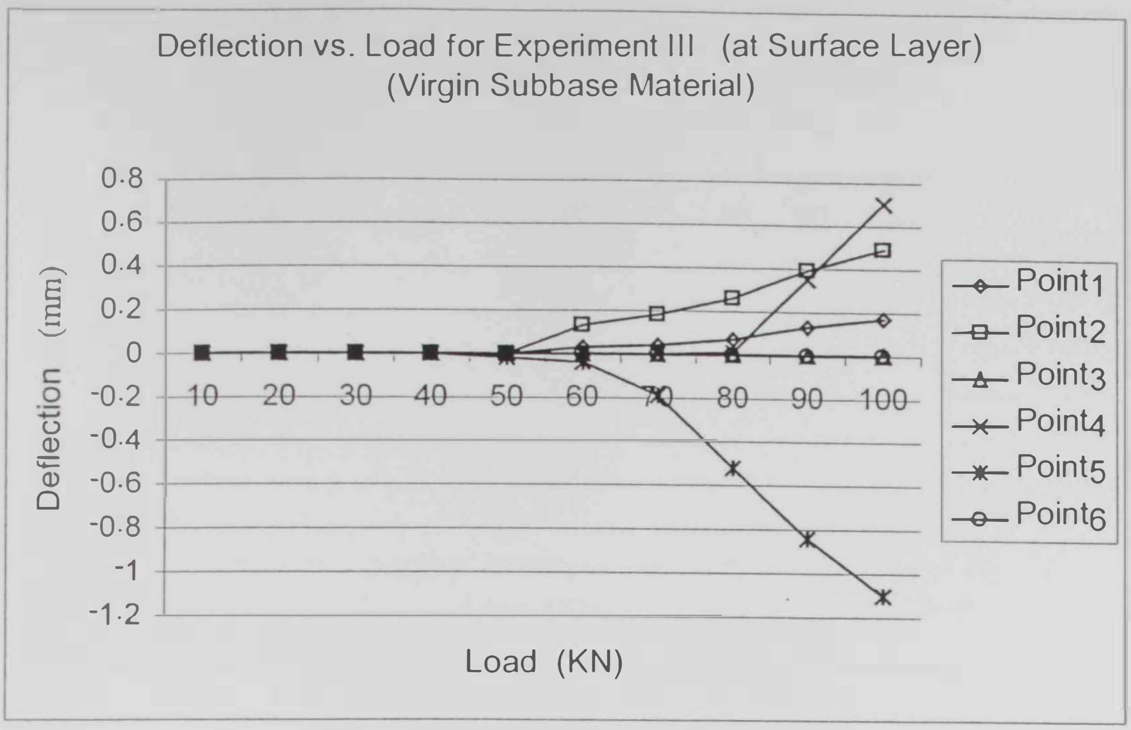
4.4 Effect of Subbase Material Types

Part of the virgin material was replaced by RCA (experiment IV) while keeping the subbase layer thickness constant (i.e. 20 cm). The outcome of this experiment and the plain virgin material experiment (experiment III) are shown in Figure 4.4 and 4.5. Comparing the two Figures, it can be easily seen that the use of RCA subbase mix resulted in lesser deformation. Results were significantly lower in the case of the RCA. The percent reduction in deformation varied from location to location. Near the center of the mold, reduction of about 57 % was recorded.

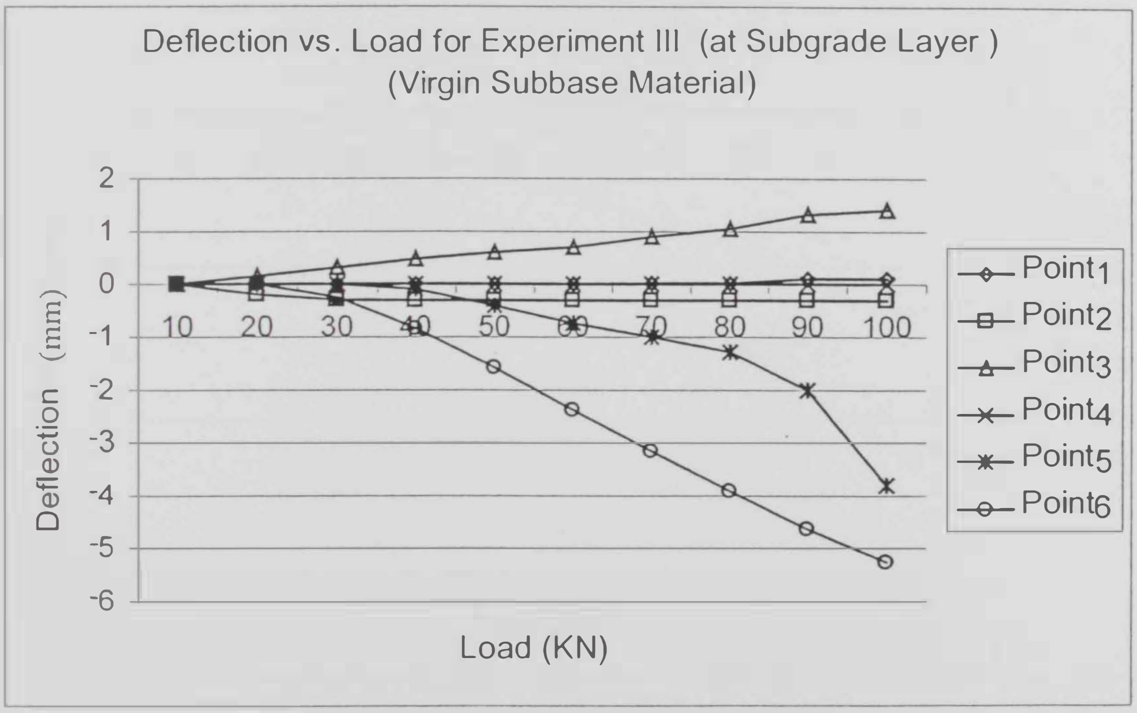
The difference in the deflection patterns of experiments III and IV could only then be attributed to the partial replacement of the 20-centimeter subbase virgin material with RCA materials. The reason for this superior action of the RCA material could be attributed to these factors:

1) The fact that RCA is harder than original virgin material.

2) The cementing action of the RCA resulting from already un-hydrated cement found within RCA. This cementing action produces more rigid material causing the deformation to be lower.

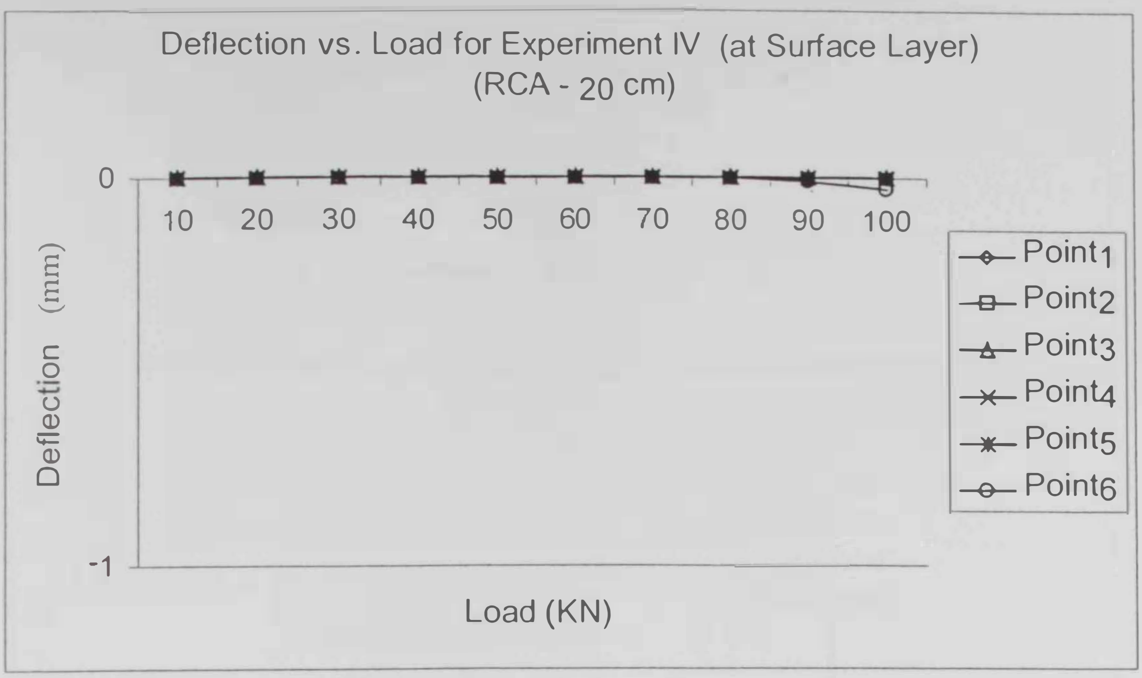


(a)

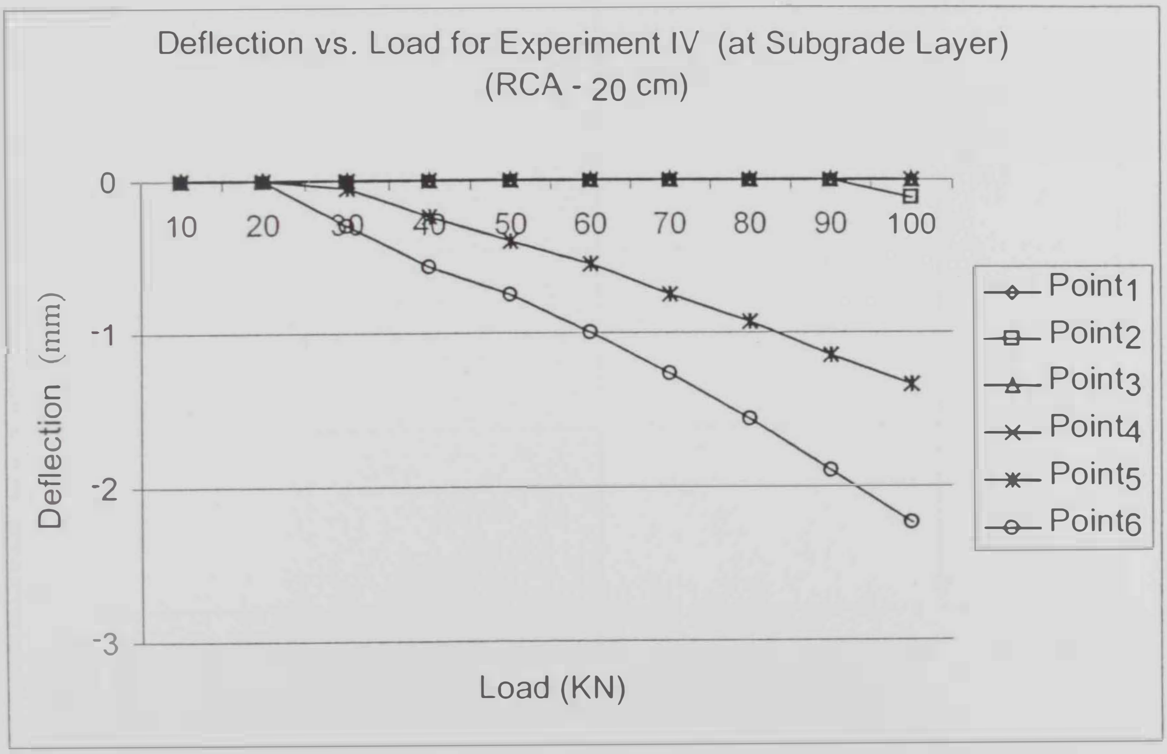


(b)

Figure (4.2): Deflection vs. Load for the Virgin Subbase Material: (a) Surface Layer, (b) Subgrade Layer

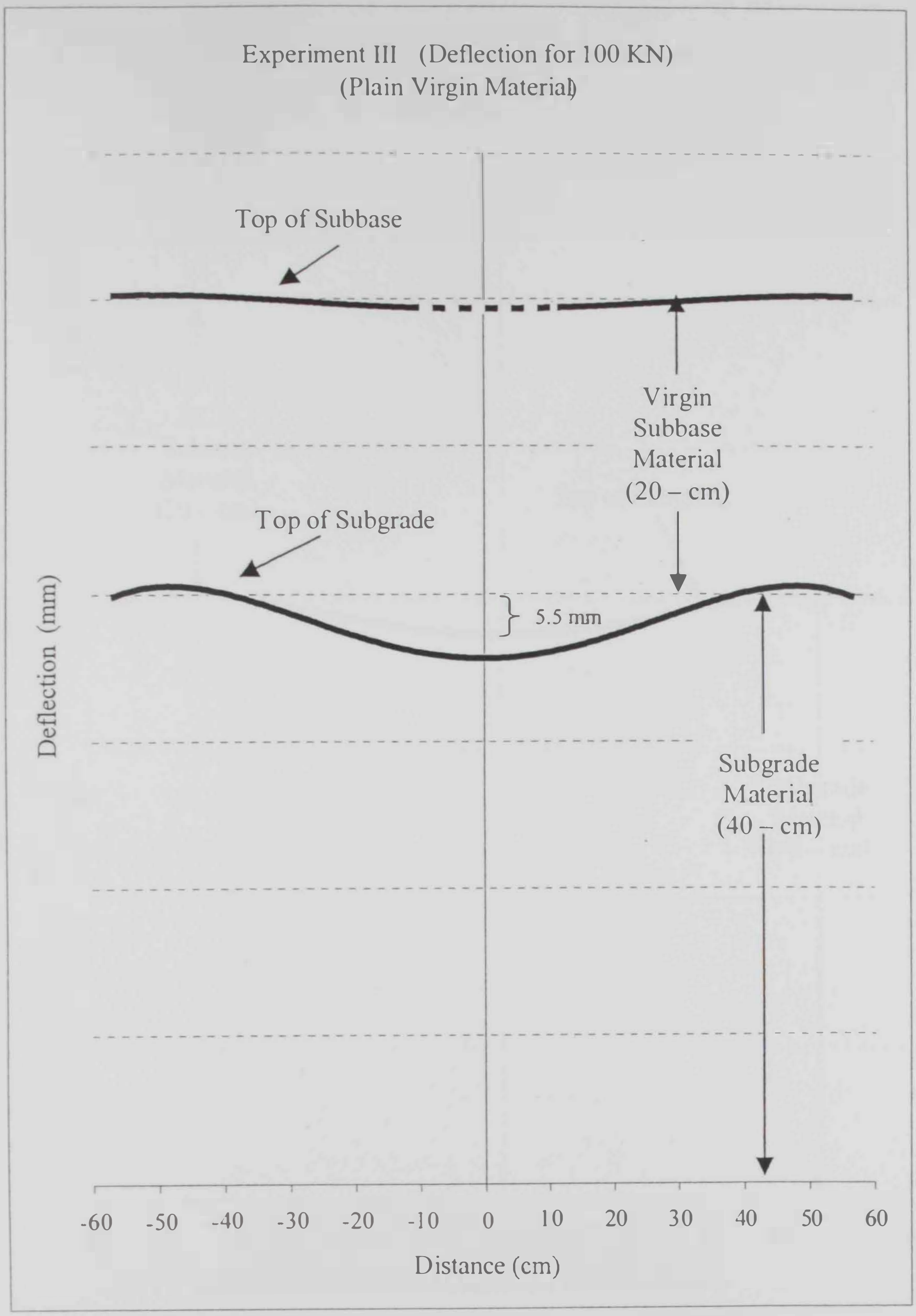


(a)



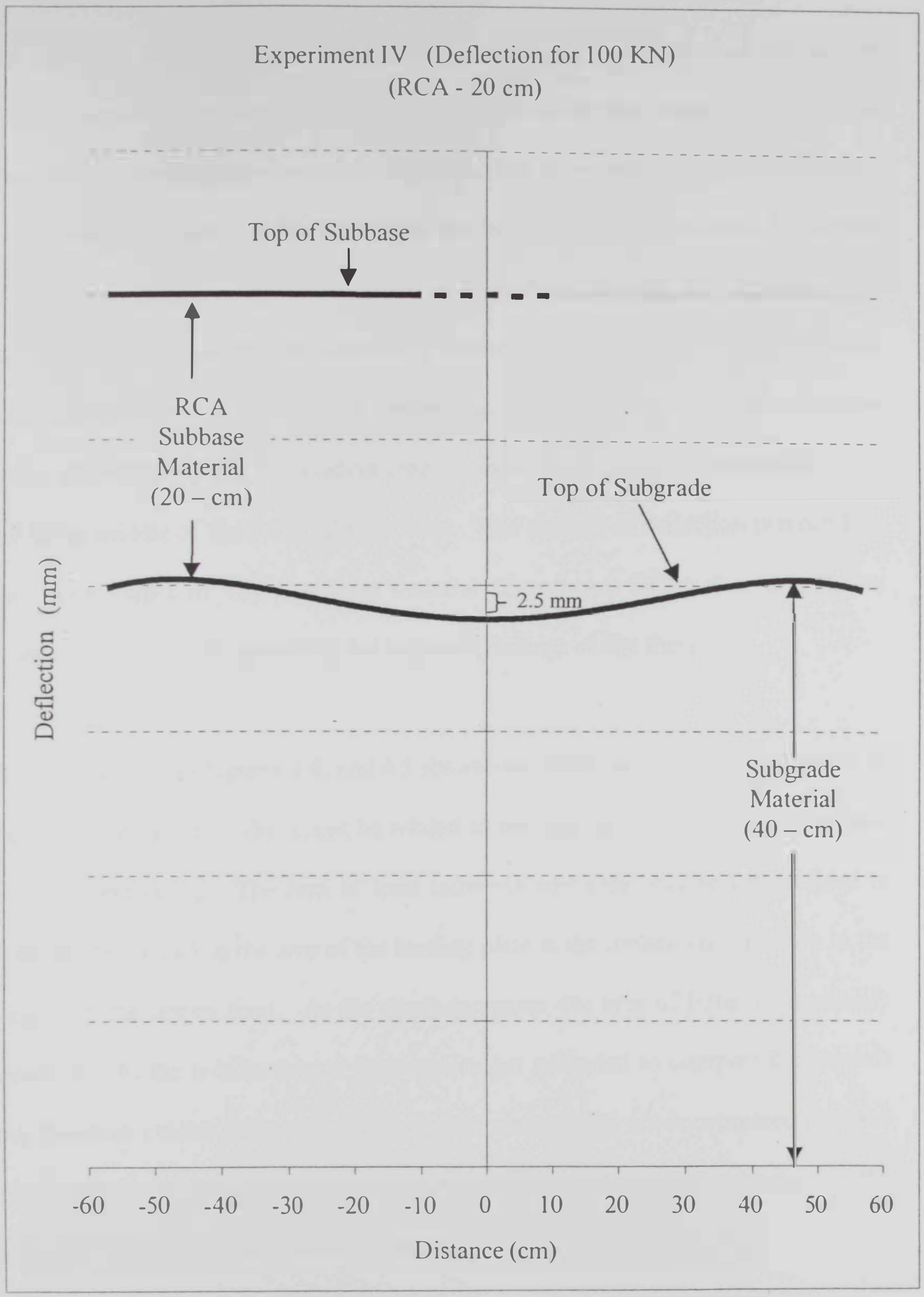
(b)

Figure (4.3): Deflection vs. Load for the RCA Subbase Material: (a) Surface Layer, (b) Subgrade Layer



*Magnified scale to illustrate small deflection values

Figure (4.4): Deflection for Experiment III at 100 KN (Plain Virgin Material)

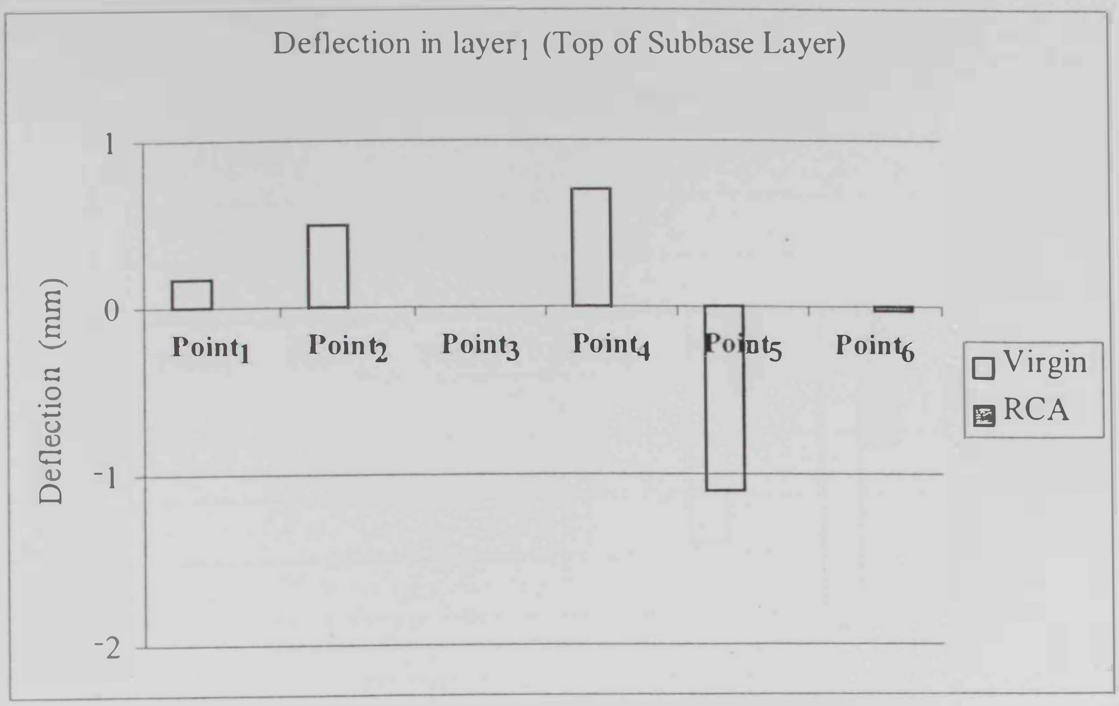


*Magnified scale to illustrate small deflection values

Figure (4.5): Deflection for Experiment IV at 100 KN (RCA – 20 cm)

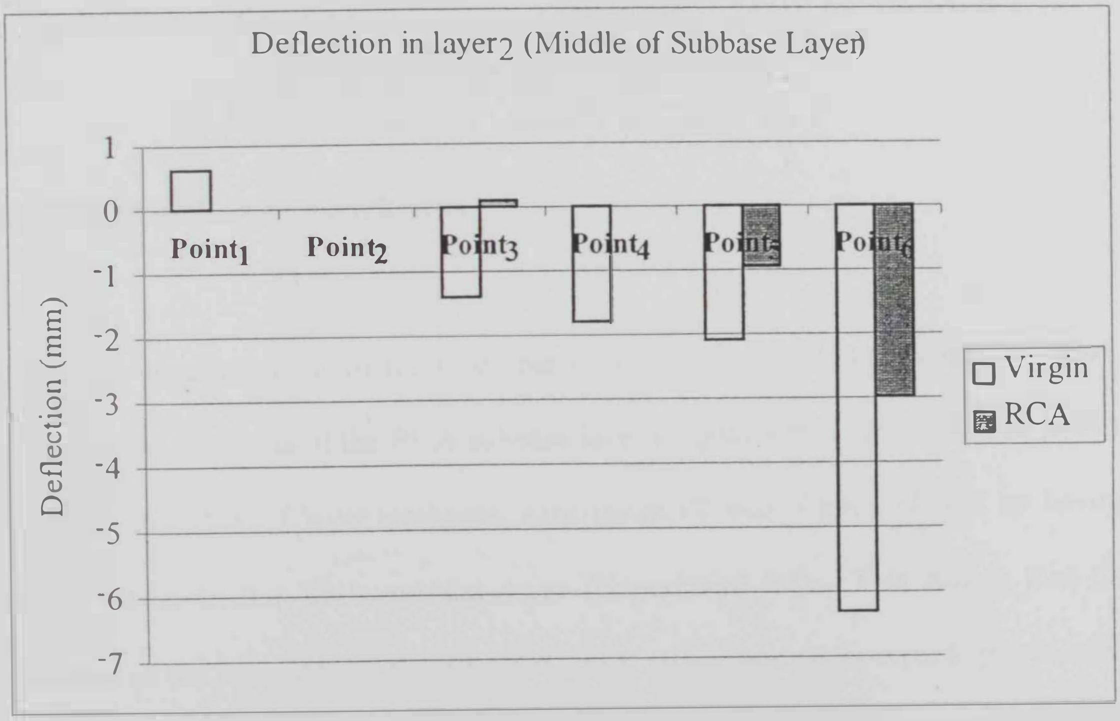
The bar chart in Figure 4.6-a shows a very small amount of deflection (at the top layer) in experiment IV and only at the point nearest to the load center (point 6). The other points have no deflection values recorded. The data value of the same point was not recorded in experiment III. The other top layer points of experiment III showed noticeable deflection values as compared to those of experiment IV. Figures 4.6-b and 4.6-c clearly illustrate the substantial difference in deflection amounts between the two experiments. With the RCA subbase material (Experiment IV), the deflection occurs only at points near the loading plate (points 5 & 6) at the top of subgrade layer and in the middle of the RCA subbase layer. This amount of deflection is much less than those values of virgin subbase material (Experiment III) at the same points location. These results agree with the expected findings of this thesis.

The surface layer in Figures 4.4, and 4.5 shows very small deflections as compared to the underneath layers. This could be related to the way stresses dissipate throughout the pavement layers. The area of load influence (the area over which the load is distributed) is equal to the area of the loading plate at the surface layer (shown in the figures by the dotted line). As the depth increases, the area of influence gradually increases. At the bottom layers, more points get subjected to compression stresses and therefore exhibit deflection. The highest stress levels are encountered near the top, and they diminish as depth increases. This explains the reduction in the deflection values with the increase of depth.



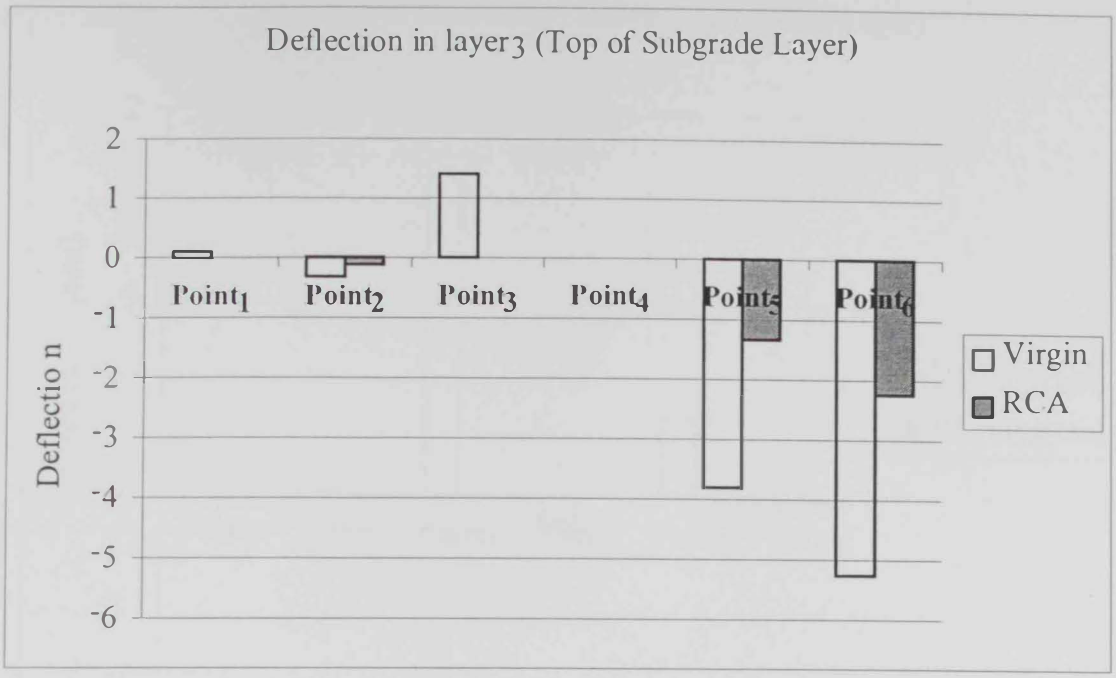
Deflection in layer1 (Top of Subbase Layer)
1
0
-1
-2
Deflection (mm)
Point1
Point2
Point3
Point4
Point5
Point6
Virgin
RCA

(a)



Deflection in layer2 (Middle of Subbase Layer)
1
0
-1
-2
-3
-4
-5
-6
-7
Deflection (mm)
Point1
Point2
Point3
Point4
Virgin
RCA

(b)

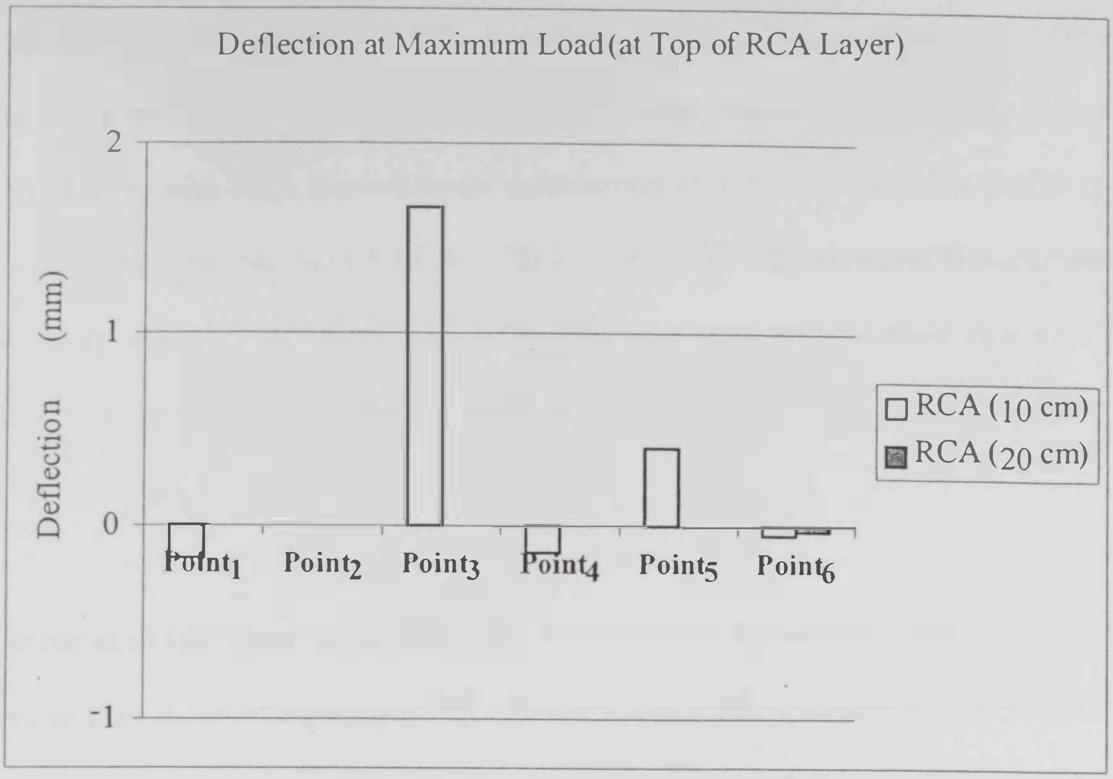


(c)

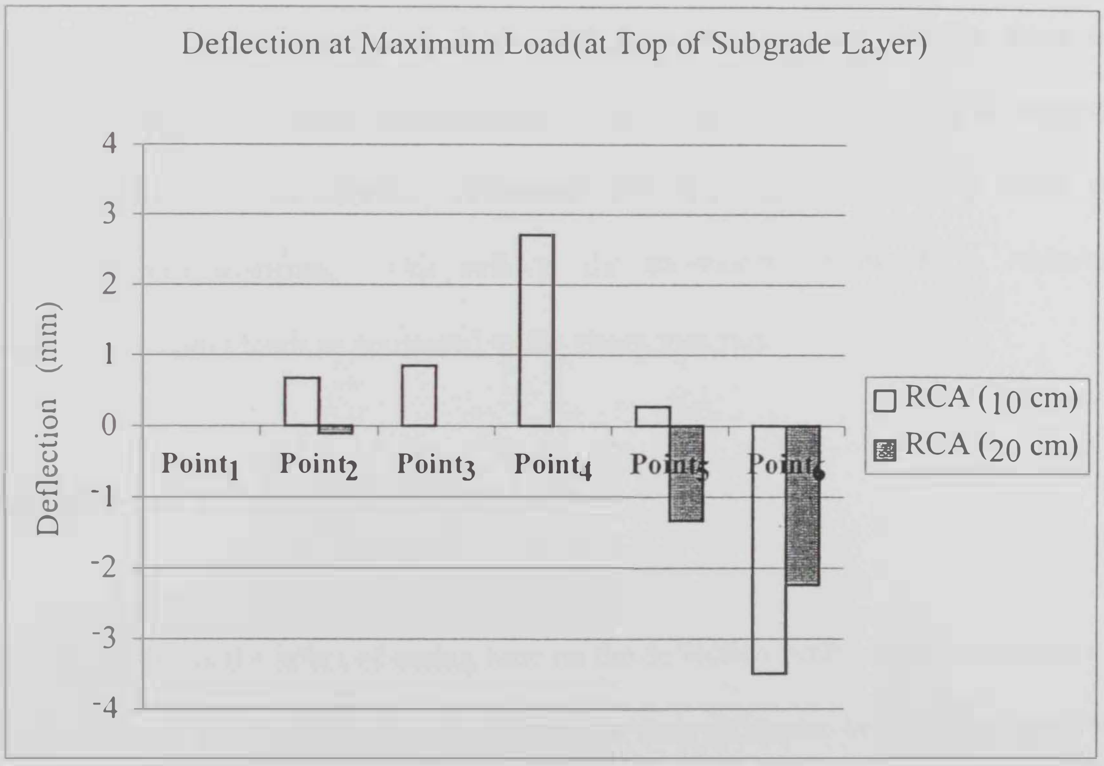
Figure (4.6): Deflection at 100 KN for Experiments III & IV for: (a) Layer 1, (b) Layer 2, (c) Layer 3

4.5 Effect of Layer Thickness

Due to the superior action of RCA compared to virgin material, an attempt was made to reduce the thickness of the RCA subbase layer (experiment VI as compared to IV). To study the effect of layer thickness, experiment IV was slightly altered by having only a 10-centimeter RCA subbase layer (Experiment VI). This means that the thickness of the layer was reduced by 50%. All other parameters were kept constant. Reducing the thickness of the RCA layer by 50% resulted, as expected, in higher deformation results, only at the points close to the center of load application (see Figure 4.7). Maximum reduction of about 36% was seen at the center compared to the 20-centimeter RCA subbase layer.



(a)



(b)

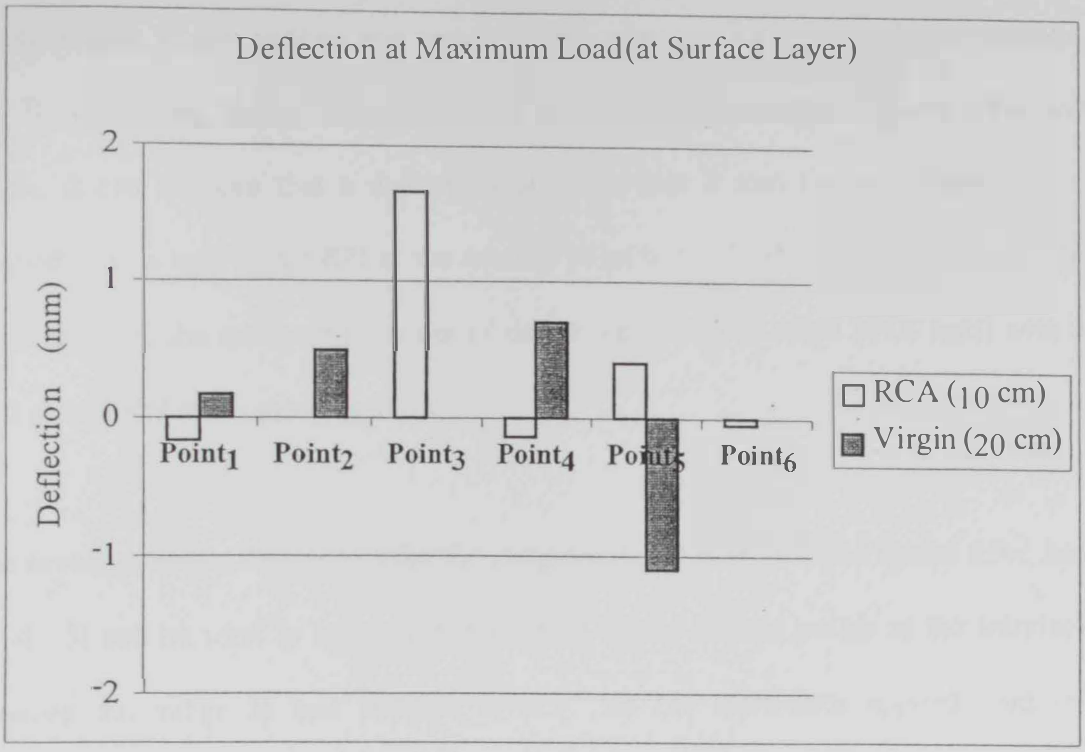
Figure (4.7): Deflection at 100 KN for Experiment IV & VI at: (a) Top Layer, (b) Top of Subgrade Layer

Although layer thickness of the RCA material was reduced in experiment VI by 50% compared to virgin material (experiment III), results remained superior (see Figure 4.8). Layers with RCA showed lower deformation values and more stable profile of surface of both layers. In fact, RCA (with ½ thickness of virgin material) lowered the results by about 33 %. Maximum reductions were seen near the mold center (3.5 mm). The reason for this behavior could again be attributed to the cementing action of the material.

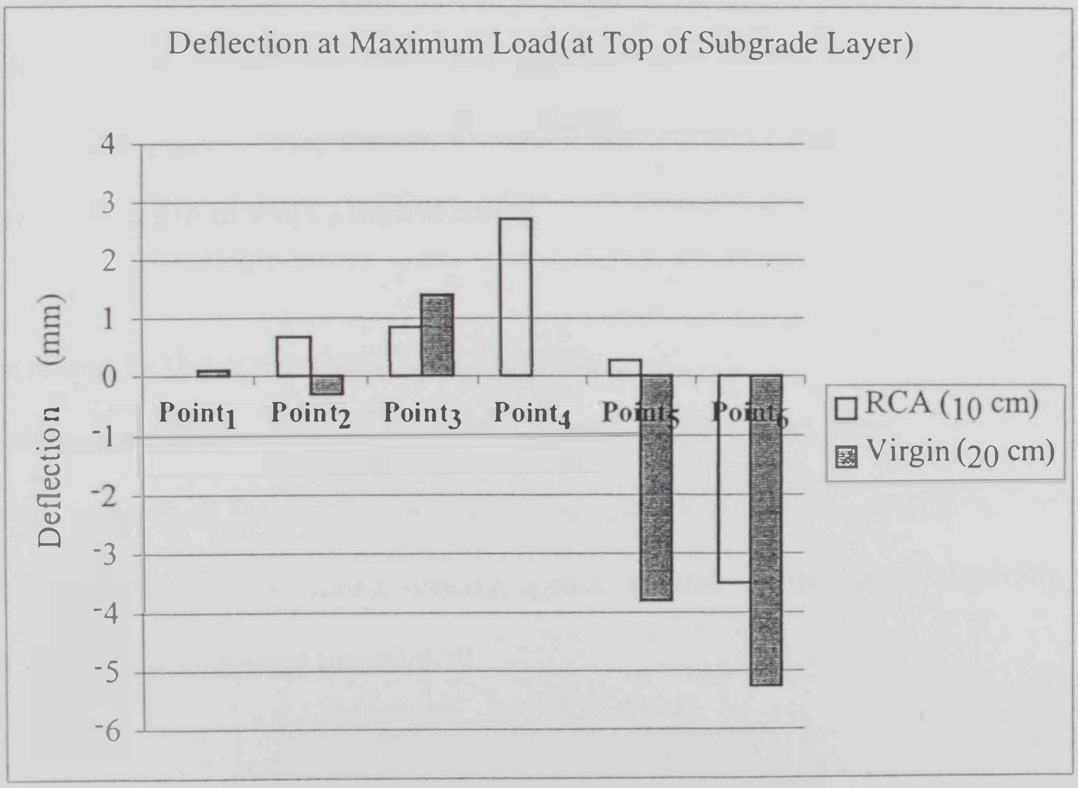
The bar chart (in Figure 4.8-a) shows that the deflection amounts in experiment III are greater than those of experiment VI. Points 3 and 6 are ignored from the analysis because their corresponding values of experiment III were not measured. Figure 4.8-b shows clearly that the deflection amount (at the top of the subgrade layer – near the interface with the subbase material) is much less in experiment VI than those in experiment III. Even when reducing the RCA layer thickness to 50 % of its original thickness, it still shows better performance than the virgin material in terms of deflection measurements. This reflects the superiority of the RCA material performance under loads as compared to the virgin material.

4.6 Effect of RCA Curing Time

Figure 4.9 shows the effect of curing time on the deflection versus load diagrams. i.e., experiments V and VI. Curing time refers to the time difference between laying down the RCA layer after compaction to the time the load is applied.



(a)



(b)

Figure (4.8): Deflection at 100 KN for Experiment III & VI at: (a) Surface Layer, (b) Top of Subgrade Layer

In experiment V, curing time was one day only, where it was 21 days for experiment VI. By comparing the top layer deflection in the two experiments (Figures 4.9-a and 4.9-b), it can be seen that a deflection of more than 8 mm (in experiment V) is reached with a load of 60 KN at the nearest point to the loading plate (point 6). In experiment VI the maximum amount of deflection was very small (0.05 mm) with a load of 100 KN at the same location.

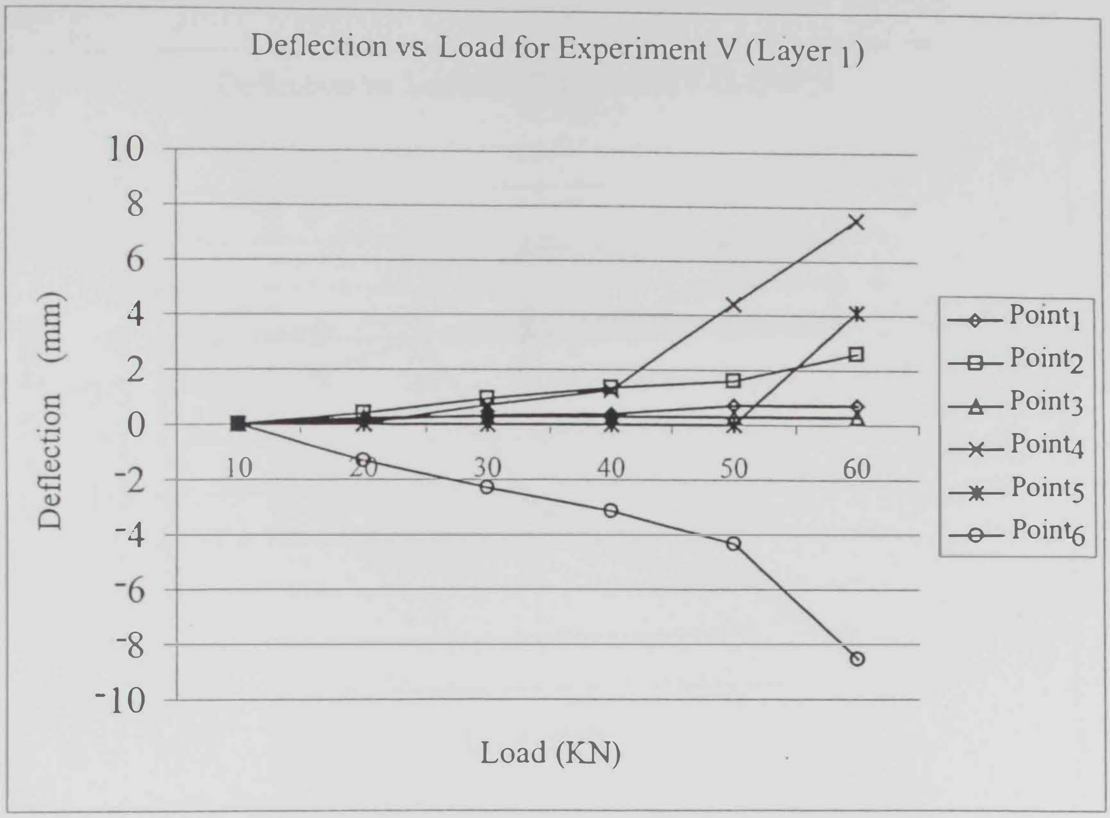
The investigation of the results for the subgrade layer is shown in Figures 4.9-c and 4.9-d. It can be used to assess the deflection values for the points at the interface between the subgrade and subbase layers. At the maximum applied load (of experiment V – at 70 KN), the deflection at the nearest point to the loading plate was 3.09 mm, whereas in experiment VI the deflection was substantially lower (1.43 mm) at the same loading level (70 KN). The maximum level of load reached for the one-day curing experiment (experiment V) was 70 KN, while it reached 100 KN without material failure in case of 21 days of curing.

The reason for this action could be attributed to:

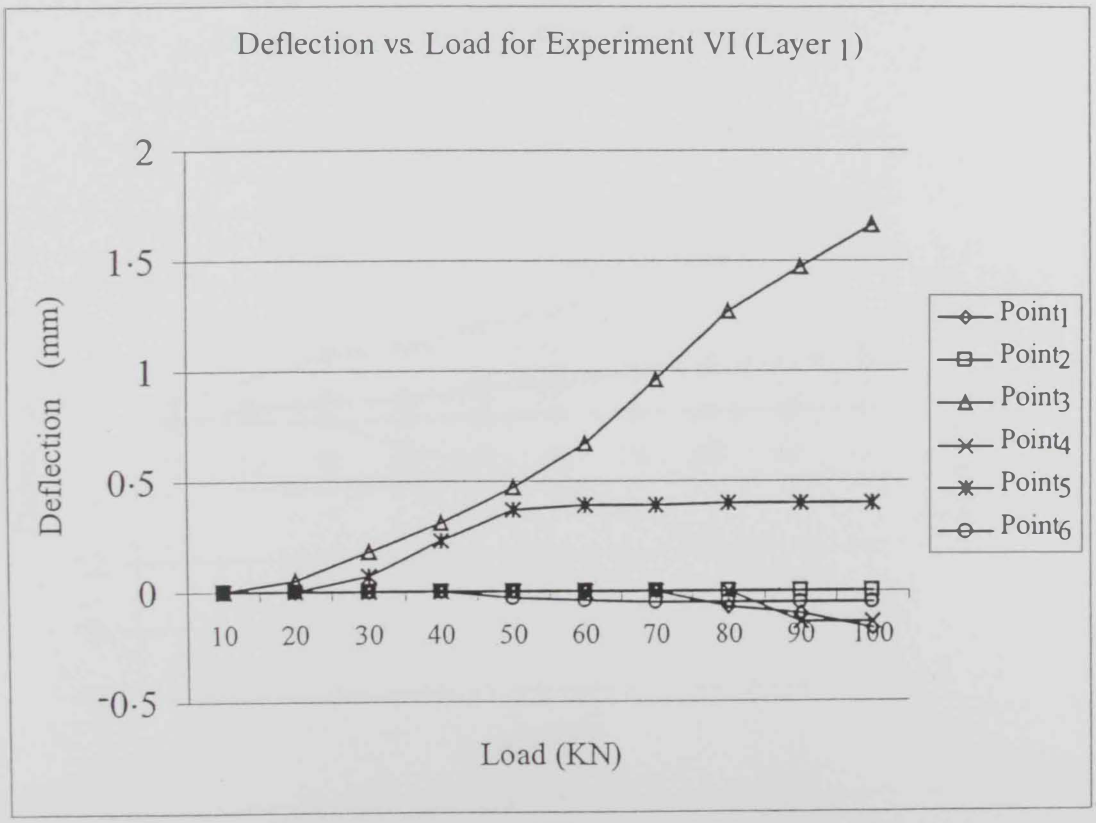
1) Not enough time was allowed for the cementing action to take place.

2) The water used in compaction was not completely dried. The cementing mortar then acted as a lubricant (not a bonding agent), and this resulted in the instability of the model V as compared to model VI.

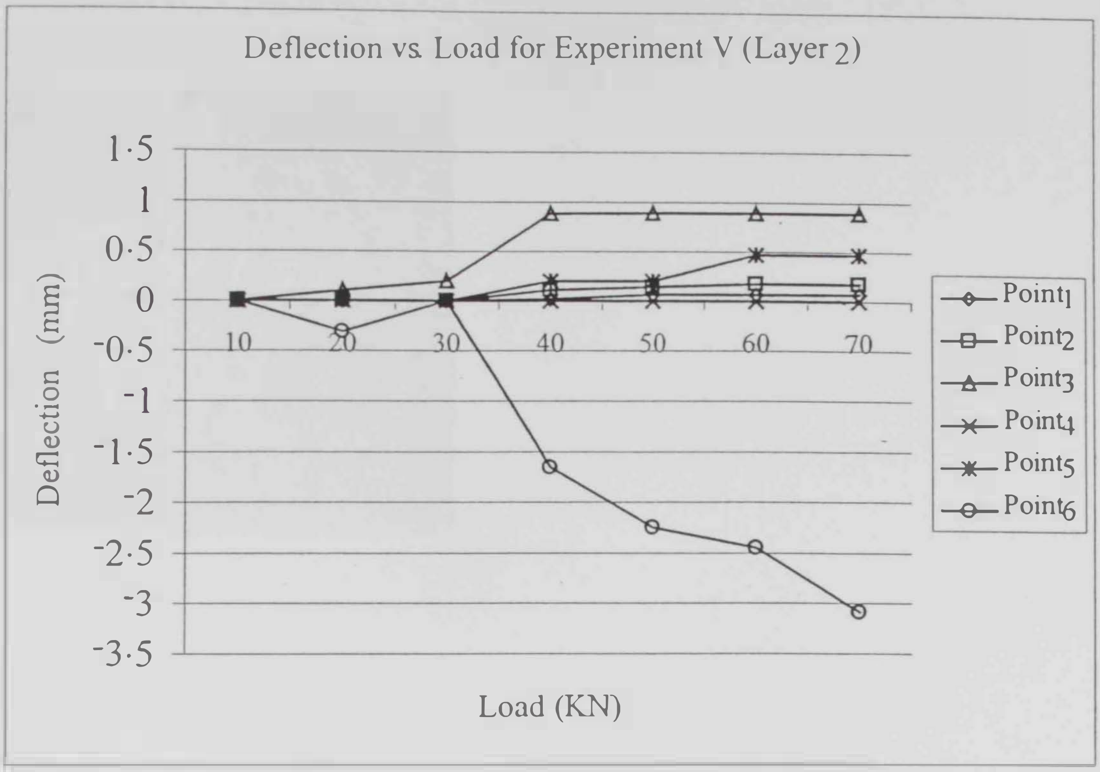
These results clearly indicate the importance of allowing enough time for the RCA material to cure, if it is to be used in the construction of highway pavements.


Deflection vs. Load for Experiment V (Layer 1)
10
8
6
4
2
0
-2
-4
-6
-8
-10
10
20
30
40
50
60
Deflection (mm)
Load (KN)
Point1
Point2
Point3
Point4
Point5
Point6

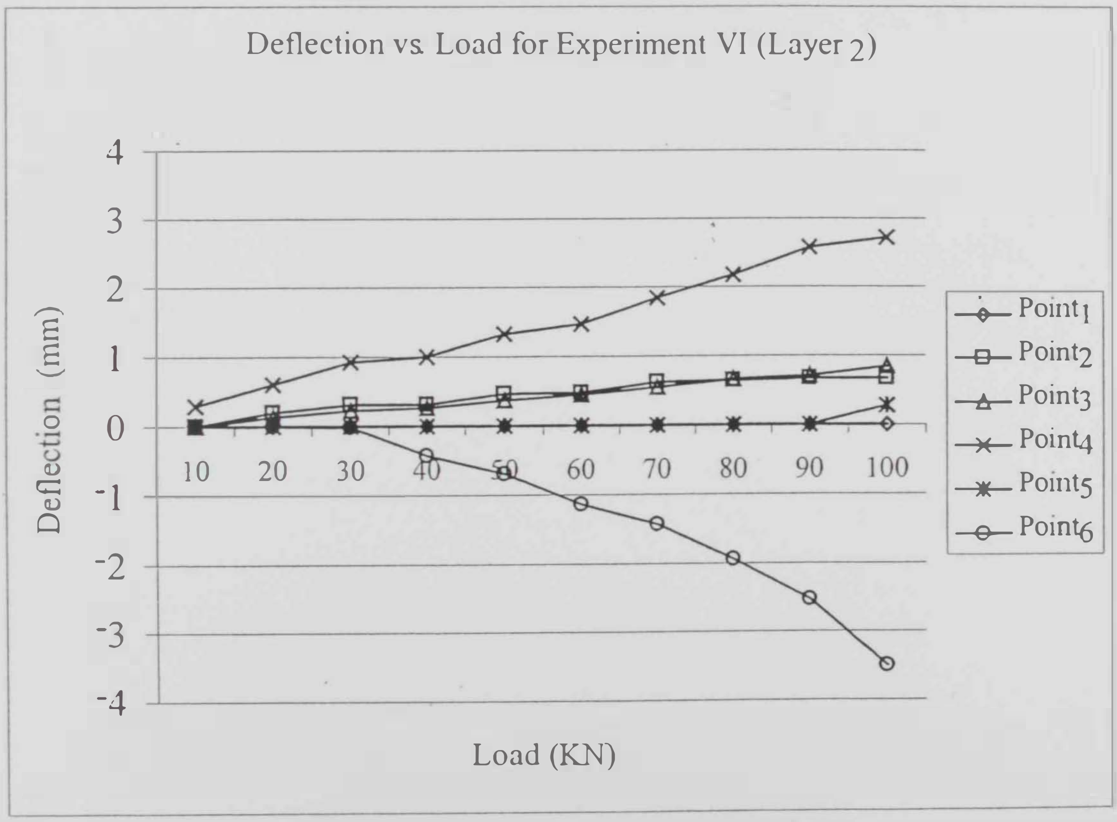
(a)


Deflection vs. Load for Experiment VI (Layer 1)
2
1·5
1
0·5
0
-0·5
10
20
30
40
50
60
70
80
90
100
Deflection (mm)
Load (KN)
Point1
Point2
Point3
Point4
Point5
Point6

(b)



(c)



(d)

Figure (4.9): Deflection Vs. Load for Experiment V & VI: (a) Exp. V – Layer 1, (b) Exp. VI – Layer 1, (c) Exp. V – Layer 2, (d) Exp. VI – Layer 2

CHAPTER FIVE

Chapter Five

General Discussion, Conclusions, and Recommendations for Further Studies

This chapter briefly highlights the conclusions of this thesis, and addresses some of the potential directions for future research. The chapter is divided into three main sections. A general discussion of the thesis forms Section 5.1. Section 5.2 summarizes the conclusions of this thesis and Section 5.3 provides suggestions for further studies.

5.1 General Discussion

The RCA material could be an attractive alternative (both economically and environmentally) if its characteristics are proven to be close to or better than those of the natural virgin material when used in pavement construction. In the UAE, RCA has been managed mainly through dumping in landfills. The properties of the RCA material that could be recycled vary from place to place. The recent construction evolution in the UAE has produced tremendous amounts of RCA that have serious implications for the environment. In addition to the scarcity of land, other problems associated with the discarding of waste concrete materials in landfills include their transportation costs and charging fees to the municipality. Thus, recycling has been gaining wider attention as a viable option for the handling of waste concrete.

The results of this study include a better understanding of the behavior of subbase layer made of a mix of RCA and virgin material. The main findings of this thesis are that the RCA subbase mix material shows better performance in term of surface deflection compared with the virgin material. In general, RCA material exhibited better performance than the virgin material under loads. It is critical to point out the importance of allowing the RCA material enough curing time. The RCA materials showed better stability under loads, probably due to the additional bonding effect caused by the small cement particles.

The acceptance of RCA as a road construction material will depend on whether it satisfies certain specifications and criteria. This may be different from country to country and also will depend on the application. The decision to use RCA in UAE road construction is debatable and will be subject to highway administration approval if proven to be an efficient alternative. The wastes concrete are available material whenever there is reconstruction projects, also it can be provided for free. Using such material required only the crushing machines. On the other hand, the virgin materials are provided from far distances; which makes the transportation cost very high in addition to the material and crushing costs. As proven in Chapter 5 RCA materials results in better performance (stronger). As such, designing highway pavement using RCA would result in thinner cross-section, and consequently smaller amount of material. This would also contribute to the savings in the case of using RCA.

There are several incentives for the consumer to use recycled aggregate in concrete. Some of these incentives include:

- Cost – The cost of RCA compares quite favorably with virgin aggregates.
- Environment - Conservation of natural resources and earth balance.
- Municipal Approval – Most municipalities allow the use of recycled aggregate if it meets all required specification.
- Waste Management – With the general need to reduce and manage waste, the use of RCA is one of the most effective ways of doing this.
- Performance – Using RCA as a subbase layer results in better performance than the virgin material.
- Availability – Waste concrete material is always available whenever there is reconstruction or other sources.

5.2 Conclusions

Following the above discussion, three main conclusions can be drawn from this thesis:

- The use of RCA to replace part of virgin subbase material improved the performance of the pavement in terms of deformation of subbase and subgrade layers. Lower surface deflection results were recorded.

- With RCA, the subbase layer can be reduced in thickness and will still result in similar or better performance than virgin subbase layer.
- When RCA is used, a sufficient curing period is required.

5.3 Recommendations for Further Studies

The framework and mold developed in this thesis suggest an avenue of research in the field of material testing. Possible areas for future research include the following:

- There was a difficulty in fixing the eighteen dial gauges which distributed to represent the whole area. The loading plate was a square plate. It would be better if we use a round plate, so that the gauges can be fixed in one line to represent the whole area.
- The sources of RCA material in this study were the testing cubes from different projects in Al Ain city. Other concrete sources with known strength (low, medium, and high strength) and age might be used and compared together.
- The results of this study lead to a better understanding of the behavior of RCA subbase mix and it indicated encouraging results. Other research might be needed to test the suitability of the RCA material in other layers of the pavement or in any other construction projects.
- One of the most interesting concepts to study is the effect of possibly using different combinations of virgin and RCA material. It is also essential to study the effect of RCA grading size.

- There is an amount of unhydrated cement particles in old concrete. It is important to study the amount of cement particles that can be triggered to react further.
- The bonding between the RCA material layers and the upper layers might have implications for the performance of the pavement over long time periods. It is strongly suggested that the long-term effect and behavior of the RCA material be studied via an actual cross-section. The long-term observation of the real cross section, and possibly the development and progression, or the types and severity of the distresses are by far the best indicators of the RCA material performance.
- The effect of temperature, cyclic loading, and long term loading (such in parking areas) could be studied to evaluate the performance of the RCA material at these different conditions.

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APPENDIX
A

ANNUAL REPORT FOR THE YEAR 1993

WASTE MANAGEMENT SECTION

FROM 01/01/1993 TO 30/12/1993

WASTE TREATMENT UNIT

DATE 10/01/1994

DISPOSAL SITE OR DISCHARGE POINT	SOURCE	G.WASTE		B.WASTE		GARDEN WASTE		COV.MATERIAL		LIQUID WASTE		IND.WASTE	
		WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGTH TONS	TRIPS	WEIGHT TONS	TRIPS	CUM / (M)	TRIPS
AL-QUSAIS	D.M	383261.44	55359	12457.04	1254	22216.02	9425	264376.59	15370	23477.68	1753	------	-------
	PVT	98065.2	52069	633345.97	41712	1587.02	966	2053.34	95	253075.66	14473	-------	-------
J.ALI	D.M	3797.76	2203	-------	-------	2539.05	1276	67826.65	3901	120.54	9	255.57	33
	PVT	81940.64	24068	344428.67	15877	1585.92	1837	-------------	-------	67863.84	4036	11730.31	1086
AWIR ROAD B.WASTE	D.M	195.32	145	3621.47	407	--------	--------	--------	--------	45535.70	3400	------	------
	PVT	--------	-------	705253.34	34701	-----	--------	104.4	5	61637.96	3402	-----	-------
AWIR AREA	D.M	9037.45	5413	--------	------	3141.73	1329	-------	--------	20665.18	1543	---------	---------
	PVT	9824.65	6418	---------	----------	----------	--------	3284.91	161	---------			
HATTA	D.M	5040.06	3800	THE SITE IS NOW FUNTIONING AS A TRANSFER						42281.25	3157	---------	----------
	PVT	438.2	626	STATION FROM 01/11/93. ONLY LIQUID WASTE IS DISCHARED REST OF THE WASTE IS TRANSFERED TO AWIR AREA SITE .									
AL- QUSAI DISCHARGE POINT	D.M						---------	------		111436.02	8471	--------	---------
	PVT	BOTH THE POINTS ARE NOW RUN BY DRAINAGE &					---------	--------		632502.2	39839	----------	---------
AL- QUOZ DISCHARGE POINT	D.M									177832.14	13204	---------	---------
	PVT	IRRIGATION DEPARTMENT I.E. FROM 01-07-1993					-------	-------		509295.43	35817	-------	----------
TOTAL	D.M	401332.03	66920	16078.51	1661	27896.8	12030	332203.25	19271	417839.57	31275	255.57	33
	PVT	190268.69	83181	1683027.97	92290	3172.94	2803	5422.65	261	1524374.87	97.567	11730.31	1086
G.TOTAL	D.M+PVT	591600.72	150101	1699106.48	93951	31069.74	14833	337625.9	19532	1942214.44	128842	11985.88	1119

ANNUAL REPORT FOR THE YEAR 1994 *WASTE MANAGEMENT SECTION*

FROM 01/01/1994 TO 25/12/1994 *WASTE TREATMENT UNIT* *DATE 25/12/1994*

DISPOSAL SITE	SOURCE	G.WASTE		B.WASTE		GARDEN WASTE		COV.MATERIAL		LIQUID WASTE		IND.WASTE	
		WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGTH TONS	TRIPS	WEIGHT TONS	TRIPS	CUM / (M)3	TRIPS
AL-QUSAIS	D.M	366286.1	54068	18885.21	2302	18043.01	8506	246282.01	15665	27676.39	2032	-------	-------
	PVT	110197.56	58606	794266.19	51208	559.96	431	----------		319657	18454	-------	-------
JEBEL ALI	D.M	3775.16	2213	16.84	2	1871	769	81283.4	5098	326.89	24	7.495	3
	PVT	88825.22	26552	368337.07	17423	1015.14	1644	----------	-------	27524.29	1830	9739.025	891
AWIR ROAD B.WASTE	D.M	120.01	103	2067.73	234	--------	--------	---------	--------	45927.54	3372	------	------
	PVT	------	------	859922.82	43969	-----	--------	----------		21228.54	1506	-----	-------
AWIR AREA	D.M	9725.43	5753	------	------	6202.45	2619	------	------	19885.59	1460	----------	---------
	PVT	10844.41	7240	--------	----------	---------	--------	------	---------	-------	-------	--------	---------
TOTAL	D.M	379506.7	62137	20969.78	2538	26116.46	11894	327565.45	20763	93816.4	6888	7.495	3
	PVT	209867.19	92398	2022526.07	112605	1575.1	2075	------		368409.83	21790	9739.025	891
G. TOTAL	D.M+PVT	589373.89	154535	2043495.85	115143	27691.56	13969	327565.45	20763	462226.23	28678	9746.52	894

ANNUAL REPORT *WASTE MANAGEMENT SECTION*

FROM 26/12/1994 TO 31/12/1995 *WASTE TREATMENT UNIT* *DATE 15/01/1996*

DISPOSAL SITE	SOURCE	GENERAL WASTE		BUILDING WASTE		GARDEN WASTE		COV.MATERIAL		LIQUID WASTE		DIFFICULT/HAZARDOUS WASTE	
		WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGTH TONS	TRIPS	WEIGHT TONS	TRIPS	TONS	TRIPS
AL-QUSAIS	D.M	363448.88	46585	8517.12	1103	20741.47	8914	191078.33	11889	47714.52	3926	-------	-------
	PVT	133058.19	57386	287352.97	18536	1964.66	1188	79848.6	3130	146331.15	8723	-------	-------
JEBEL ALI	D.M	3207.63	2018	--------	------	2195.06	1020	74399.83	4615	1089.6	80	77.64	16
	PVT	102014.24	26218	343757.6	16398	1088.22	1792	------------	-------	1498.23	66	23209.681	2221
AWIR ROAD B.WASTE	D.M	29.08	27	11899.51	1579	--------	--------	---------	--------	57518.40	4223	------	------
	PVT	--------	-------	2027289.77	112570	-----	--------	----------	---------	12085.72	704	-----	-------
AWIR AREA	D.M	8110.72	5426	--------	------	5567.84	2658	--------	--------	----------	--------	----------	---------
	PVT	11873.97	7086	---------	----------	----------	--------	---------	----------	---------	--------	--------	----------
TOTAL	D.M	374796.31	54056	20416.63	2682	28504.37	12592	265478.16	16504	106322.52	8229	77.64	16
	PVT	246946.4	90690	2658400.34	147504	3052.88	2980	79848.6	3130	159915.1	9493	23209.681	2221
G.TOTAL	D.M+PVT	621742.71	144746	2678816.97	150186	31557.25	15572	345326.76	19634	266237.62	17722	23287.321	2237

ANNUAL REPORT *WASTE MANAGEMENT SECTION*

FROM 01/01/1996 TO 31/12/1996 *WASTE TREATMENT UNIT* *DATE 06/01/1997*

DISPOSAL SITE	SOURCE	GENERAL WASTE		BUILDING WASTE		GARDEN WASTE		COV.MATERIAL		LIQUID WASTE		DIFFICULT/HAZARDOUS WASTE	
		WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGTH TONS	TRIPS	WEIGHT TONS	TRIPS	TONS	TRIPS
AL-QUSAIS	D.M	363820.82	45287	11021.38	1561	21074.82	9135	186382.18	11563	90624.72	7176	-------	-------
	PVT	153761.64	62976	375845.83	27611	1090.73	846	12396.79	465	169385.73	9198	-------	-------
JEBEL ALI	D.M	3655.33	2081	-------	-------	1180.22	608	48629.8	3010	12144.74	904	7.333	18
	PVT	102011.53	27908	215652.2	10444	719.65	904	-------	-------	-------	-------	98628.599	6210
AWIR ROAD B.WASTE	D.M	30.49	66	6278.83	849	-------	-------	-------	-------	53554.89	3932	-------	-------
	PVT	-------	-------	1733421.34	93692	-------	-------	-------	-------	12912.01	582	-------	-------
AWIR AREA	D.M	7955.5	5037	-------	-------	4296.69	2352	-------	-------	-------	-------	-------	-------
	PVT	12517.34	6780	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
HATTA	D.M	2478.85	4259	-------	-------	-------	-------	-------	-------	19339.41	2442	-------	-------
	PVT	101.68	92	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
TOTAL	D.M	377940.99	56730	17300.21	2410	26551.73	12095	235011.98	14573	175663.76	14454	7.333	18
	PVT	268392.19	97756	2324919.37	131747	1810.38	1750	12396.79	465	182297.74	9780	98628.599	6210
G.TOTAL	D.M+PVT	646333.18	154486	2342219.58	134157	28362.11	13845	247408.77	15038	357961.5	24234	98635.932	6228

ANNUAL REPORT *WASTE MANAGEMENT SECTION*

FROM 01/01/1997 TO 31/12/1997 *WASTE TREATMENT UNIT* *DATE 03/01/1998*

DISPOSAL SITE	SOURCE	GENERAL WASTE		BUILDING WASTE		GARDEN WASTE		COV.MATERIAL		LIQUID WASTE		DIFFICULT/HAZARDOUS WASTE	
		WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGTH TONS	TRIPS	WEIGHT TONS	TRIPS	TONS	TRIPS
AL-QUSAIS	D.M	379805.45	45111	7032.86	836	28870.03	10103	208243.47	13394	75158.45	6175	------	-------
	PVT	206565.76	79442	268183.51	24613	2825.95	1974	-------	-------	146808.31	7647	------	-------
JEBEL ALI	D.M	4437.88	2219	-------	-----	482.82	277	40626.66	2624	14294.46	1050	36.925	57
	PVT	95426.67	27538	----------	-------	289.93	273	-------------	-------	------------	--------	92284.242	5689
AWIR ROAD B.WASTE	D.M	110.59	176	12421.6	1272	--------	--------	---------	-------	38599.81	2834	------	-----
	PVT	-------	------	2615377.86	140095	-----	--------	----------	-------	18500.85	815	----	-------
AWIR AREA	D.M	6146.14	3901	------	------	6770.86	3130	--------	-------	81.72	6	----------	---------
	PVT	12025.25	6582	-------	----------	208.29	72	---------	----------	------	---------	--------	----------
HATTA	D.M	2841.33	4523	--------	------	--------	-------	-------	-------	21448.3	2733	------	-----
	PVT	-------	------	-------	-------	-------	--------	----------	------	-----	-----	-------	-------
TOTAL	D.M	393341.39	55930	19454.46	2108	36123.7	13510	248870.13	16018	149582.76	12798	36.925	57
	PVT	314017.68	113562	2883561.37	164708	3324.17	2319	----------	--------	165309.16	8462	92284.242	5689
G.TOTAL	D.M+PVT	707359.07	169492	2903015.83	166816	39447.87	15829	248870.13	16018	314891.92	21260	92321.167	5746

ANNUAL REPORT *WASTE MANAGEMENT SECTION*

FROM 01/01/1998 TO 31/12/1998 *WASTE TREATMENT UNIT* *DATE 02/01/1999*

DISPOSAL SITE	SOURCE	GENERAL WASTE		BUILDING WASTE		GARDEN WASTE		COV.MATERIAL		LIQUID WASTE		DIFFICULT/HAZARDOUS WASTE	
		WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGTH TONS	TRIPS	WEIGHT TONS	TRIPS	m^3	TRIPS
AL-QUSAIS	D.M	408918.35	49619	4261.11	650	50918.99	13884	223780.66	14649	64194.36	5785	-------	-------
	PVT	244925.36	79611	246220.34	21524	6469.71	2746	4853.02	193	33072.73	2419	-------	-------
JEBEL ALI	D.M	4876.46	2255	-------	-------	1443.82	519	43715.36	2943	14531.46	1080	802.61	327
	PVT	104819.92	26350	875.68	52	2689.86	409	-------	-------	385.9	17	82751.413	5800
AWIR ROAD B.WASTE	D.M	115.39	155	15227.59	1664	29.73	9	303.03	33	23263.41	1708	-------	-------
	PVT	-------	-------	2704661.43	155909	-------	-------	-------	-------	17689.09	786	-------	-------
AWIR AREA	D.M	7279.68	3418	-------	-------	12894.22	359	-------	-------	1184.96	87	-------	-------
	PVT	13853.59	6174	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
HATTA	D.M	2950.67	3920	-------	-------	2122.18	829	-------	-------	18949.41	2384	-------	-------
	PVT	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
TOTAL	D.M	424116.08	59367	19488.7	2314	67408.94	18500	267799.05	17625	122123.6	11044	802.61	327
	PVT	363623.34	112135	2951757.45	177485	9159.57	3155	4853.02	193	51147.72	3222	82751.413	5800
G.TOTAL	D.M+PVT	787739.42	171502	2971246.15	179799	76568.51	21655	272652.07	17818	173271.32	14266	83554.023	6127

ANNUAL REPORT

WASTE MANAGEMENT SECTION

FROM 01/01/1999 TO 31/12/1999

WASTE TREATMENT UNIT

DATE 03/01/2000

DISPOSAL SITE	SOURCE	GENERAL WASTE		BUILDING WASTE		GARDEN WASTE		COV.MATERIAL		LIQUID WASTE		DIFFICULT/HAZARDOUS WASTE	
		WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGHT TONS	TRIPS	WEIGTH TONS	TRIPS	WEIGHT TONS	TRIPS	m^3	TRIPS
AL-QUSAIS	D.M	448487.25	53154	12669.41	1269	43612.16	11727	192102.06	12730	69004.81	6149	-------	-------
	PVT	272209.3	91941	264047.74	23662	5110.54	2375	197.13	12	49204.24	3217	-------	-------
JEBEL ALI	D.M	5630.84	2290	56.27	4	468.06	231	48113.66	3060	15929.35	1185	794.54	217
	PVT	102203.6	26515	115.85	7	1259.4	251	-------	-------	-------	-------	70673.780	3797
AWIR ROAD B.WASTE	D.M	152.29	201	19689.86	1795	-------	-------	158.8	9	23971.67	1760	------	------
	PVT	-------	-------	2783867.68	172775	-----	-------	7504.94	-------	1906.81	84	-----	-------
AWIR AREA	D.M	12392.38	3297	-------	-------	12951.47	3226	--------	497	163.44	12	----------	----------
	PVT	16595.45	6324	-------	----------	-------	-------	-------	-------	---------	-------	--------	----------
HATTA	D.M	5508.12	4054	-------	------	4320.55	1445	-------	-------	23780.99	2648	-------	-------
	PVT	--------	-------	----------	-------	-------	--------	-------	--------	-------	-----	-------	-------
	D.M	472170.88	62996	32415.54	3068	61352.28	16629	247879.46	16296	132850.26	11754	794.54	4014
TOTAL	PVT	391008.35	124780	3048031.27	196444	6369.94	2626	197.13	12	1111.05	3301	70673.780	-------
G.TOTAL	D.M+PVT	863179.23	187776	3080446.81	199512	67722.22	19255	248076.59	16308	133961.31	15055	71468.320	4014

الخلاصة

مع تطور الحياة الحديثة ، هناك إجماع من المسئولين وصانعي القرار على أهمية الحفاظ على البيئة وإيجاد حلول مناسبة أو بدائل أخرى للموارد الطبيعية المستنفذة ، وذلك يمكن تحقيقه باستغلال أفضل للمواد الطبيعية وإعادة استخدامها – خاصة - إذا كانت من المواد القابلة للنفاذ والتي تؤثر على التوازن البيئي ، فإعادة التصنيع قد يكون خيارا مناسبا جدا (سواء من ناحية بيئية أو اقتصادية) إذا ثبت أن مواصفات المواد الناتجة من إعادة التصنيع تشابه إلى حد كبير مواصفات المواد الطبيعية.

إن إعادة تصنيع المواد الخرسانية وتحويلها إلى ركام قد يحقق استفادة كبيرة في مجال البناء بشكل عام وفي طبقات رصف الطرق بشكل خاص ، ومدى مناسبة هذه المواد وقدرتها على تحمل الاوزان الكبيرة الناتجة عن حركة سير المركبات سيحقق لنا الاستفادة والحفاظ على الموارد الطبيعية بشكل فعال.

الهدف الرئيسي من هذه الأطروحة هو دراسة إمكانية استخدام المواد الناتجة عن تكسير الخرسانة (Recycled Concrete Aggregate-RCA) في إحدى طبقات رصف الطرق تسمى بطبقة الأساس المساعد (Subbase Layer) على أن تكون الخواص العامة (مثل التدرج الحبيبي) للمواد الناتجة (RCA) مطابقة للخواص العامة لمواد طبقة الأساس المساعد.

لقد تم تصميم وبناء قالب خرساني مناسب لاستيعاب المواد المراد اختبارها تحت أحمال مختلفة وتقييم أدائها ومقارنتها ببعضها البعض ، وقد روعي في التصميم أن يكون القالب بقياسات كبيرة نسبيا ليعكس الأداء الفعلي للمواد وللحصول على نتائج مقبولة.

تم تنفيذ عدة تجارب للمواد تحت أحمال مختلفة وتم تقييم أداء هذه المواد بواسطة علاقة التحميل والهبوط الناتج عن إجراء الإختبارات. وقد أشارت نتائج هذه التجارب إلى فاعلية مواد (RCA) وتفوقها على المواد الطبيعية (مواد طبقة الاساس المساعد) ، وبشكل عام فإن الهبوط الناتج في التجارب المختلفة كان أقل في حالة استخدام مواد (RCA) مما يعطي أفضلية استخدام هذه المواد عن المواد الطبيعية.

إهــــــــــــداء

إلى والدي العزيز
يامن علمني معنى الفضيلة والوعي وإدراك الذات
يامن زرع في نفسي الأمل للغد المشرق والحياة الحلوة
يامن كان وسيبقى أستاذي الأول ومرشدي ما حييت
إليك يامن أقف عاجزا عن شكره وامتناني له
إليك يامن كنت وستظل نبراسا يضيء لي دروب الحياة
إليك يامن كنت سببا لكل شيء حققته وأحققه في حياتي العلمية والعملية
إليك يا والدي الحبيب ... أهدي هذا الانجاز المتواضع

وإلى والدتي الغالية
إلى نفحة الأمل .. إلى من أنارت دربي بحبها وحنانها
إلى من كانت لي خير سند
إلى كل الاحساس الصادق
إليك والدتي الحبيبة أهدي هذا العمل المتواضع

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برنامج علوم وهندسة المواد

مدى ملائمة اعادة تصنيع المواد الخرسانية للاستخدام في منشآت الطرق

إعداد

عبدالله يوسف علي آل علي

رسالة مقدمة لعمادة الدراسات العليا
ضمن متطلبات الحصول على درجة الماجستير
في علوم و هندسة المواد

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