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Guidelines for the application of recycled concrete aggregate in the Egyptian construction Industry

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GUIDELINES FOR THE APPLICATION OF RECYCLED CONCRETE AGGREGATE IN THE EGYPTIAN CONSTRUCTION INDUSTRY

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DEDICATION

To the Egyptian Construction Industry

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ABSTRACT

The American University in Cairo

GUIDELINES FOR THE APPLICATION OF RECYCLED CONCRETE AGGREGATE IN THE EGYPTIAN CONSTRUCTION INDUSTRY

By Ahmed Moustafa Essam Aly Kamel
Under the supervision of Dr. Mohamed Nagib Abou Zeid

Construction industry is one of the most important fractions of economy worldwide. This industry consumes enormous amounts of raw materials and produces considerable waste. The optimization of construction material usage not only saves costs but also can significantly contribute towards sustainable development. The concept of recycling the construction and demolition rubble is being addressed in this study as a solution. The recycling of concrete, resulting from both the construction activities and the demolition activities, in order to be used as a source of aggregate is being focused upon in this study.

Although the idea of using recycled concrete has been implemented widely in the United States and European construction industries, one can find that the idea is still limited in most of the developing countries and Egypt is one of these nations as well. This study raises the questions of: Why the use of recycled concrete, as a source of aggregate, is still limited in Egypt and why are contractors and consultants still not encouraged to adopt the Recycled Concrete Aggregate notion even in small construction jobs? In order to address these questions, a survey has been performed within a wide range of entities that are involved in the construction and demolition waste industries in Egypt. Most of those entities have figured out that the absence of the codes of practices, field experiences, and the know-how, and the environmental and economic concerns are some of the main reasons behind these questions.

The study introduces the problem and an overview on the situation in Egypt concerning the recycling of concrete. It tackles the development of the concept of concrete recycling and presents the past world experiences in the field of concrete recycling. Moreover, a survey questionnaire is being presented covering the situation in the Egyptian construction and demolition waste industries.

It also provides the know-how of recycling concrete in the form of the layout of production plants, recycling process and crushing mechanisms. In addition, the material (Recycled Concrete Aggregate) performance and the environmental and economic concerns in recycling concrete are being tackled in the study.

The study attempts to develop both an economic model to assess the national savings that could result from recycling concrete waste and also to evaluate the viability of creating markets for recycled concrete aggregate. Moreover, some specification limits for recycled aggregate properties are being proposed by the study. The overriding conclusions of the study reveal that the government should address codes of practices and should also address taxes, levies, and subsidies in order to encourage the application of concrete recycling. Some recommendations for future studies are also presented.

Keywords: recycling, concrete, aggregate, construction, demolition waste, economic model.

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LIST OF ABBREVIATONS

RCA	:	Recycled Concrete Aggregate.
RILEM	:	International Union of Laboratories and Experts in Construction Materials, Systems and Structures. In French: [***R****éunion* ***I****nternationale des* ***L****aboratoires et* ***E****xperts des* ***M****atériaux, systèmes de construction et ouvrages*]
DIN	:	Deutsches Institut für Normung E.V.
mtpa	:	Million tons per annum
₤	:	English Pound
ha	:	Hectares
B.C.S.J	:	Building Contractors Society of Japan
ACI	:	American Concrete Institute
ASTM	:	American Society for Testing and Materials
B.S.	:	British Standards
NAHB	:	National Association of Home Builders
$	:	United States Dollars
C&DW	:	Construction and Demolition Waste
CWM	:	Construction Waste Management
MPa	:	Mega Pascal
Dfl	:	Dutch Guilders
DM	:	Deutschmark
MT	:	Metric tons

CHAPTER 1
INTRODUCTION

1.1 Overview

The construction industry is deemed to be a main industrial polluter and an exploiter of the primary resources existing on earth. As a result, the construction industry is required to rectify its course of action in order to comply with the sustainability targets recommended by the 1992 United Nations "Earth Summit" in Rio de Janeiro (Al-Ansary, 2001). The handling of the extensive quantities of wastes resulting from the construction activities represents the major hindrances in achieving a sustainable construction industry. The sustainable development – with its broad definition as "a process, which enables all people to realize their potential and improve their quality of life in ways that simultaneously protect and enhance the Earth's life-support systems," (Parkin, 2000) has become one of the main global concerns. The construction waste is defined as relatively clean, heterogeneous building materials generated from the various construction activities (Parkin, 2000). The quantity and quality of construction waste generated from any specific project would vary depending on the project's circumstances and types of materials used.

The major wastes incurred during the construction industry are usually attributed to concrete, bricks and plaster, soil, wood, plastics, and steel. According to a study published by Dundee University, figure 1.1 shows the materials that represent the major components of any waste produced during the construction or demolition of a building structure (Roos & Zilch, 1998). The mixture of crushed materials from a building construction shows that 55% is being represented by concrete, bricks and plaster, which are the elements in which cement is playing a major portion in its components. According to Roos and Zilch in their paper published by Dundee University in 1998, the old principle that the industry produces goods and the public pays for waste management is no longer valid. Thus, the construction industry is now forced to think about the recycling of building materials.

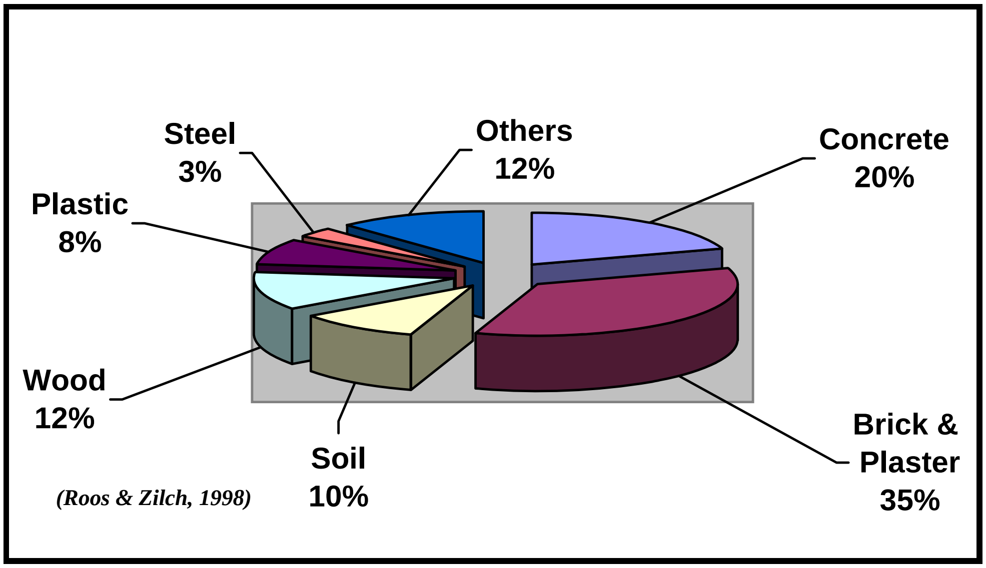


FIGURE 1.1: MAJOR COMPONENTS OF CONSTRUCTION WASTES

Over the past few decades, environmental, economic and energy considerations have encouraged the utilization of recycled concrete as aggregates in new concretes. The new concrete is referred to as “Recycled Concrete” and is usually prepared by one of two methods. The first approach is where the conventional coarse aggregates are replaced by recycled aggregates and this is referred to as partial replacement (Abou-Zeid, Shenouda, McCabe & El-Tawil, 2004). In the second approach, both the coarse and the fine aggregates are replaced by recycled aggregates and this is referred to as total replacement. The former approach is more prevailing since controlling the particle size distribution of finer particles while crushing is somehow difficult and energy consuming.

Portland cement concrete can be broken during demolition operations and crushed into a coarse granular material that can be used as a substitute for crushed virgin rock. Recycled concrete aggregate is increasingly available and is often an economical alternative to new aggregate. Project managers can ensure that their contractors are aware of opportunities to recycle this material and can require the use of recycled material in construction. Users of recycled concrete aggregate should take customary precautions to ensure that the material is suitable for the intended application.

1.2 Problem Statement

Although the idea of using recycled concrete has been implemented widely in the United States and European construction industries, one can find that the idea is still limited in most of the developing countries and Egypt is one of these nations as well. In Egypt, the quantity of building materials waste produced has been estimated as 10,000 tonnes per day, which is approximately 4.5 million tonnes per year. That is equivalent to one third of the total solid wastes generated per day in Egypt (Al-Ansary, 2001). For a typical construction project in Egypt, the fees allocated to waste handling vary between 0.5 % and 7.5 % of the overall project cost. Table 1.1 displays the estimated waste percentages from the Egyptian construction sites.

Table 1.1: Estimated Range of Wastes by Material Type from the Egyptian Construction Sites, (Al-Ansary, 2001)

Material	Minimum	Average	Maximum
Wood/Lumber	7%	11.5%	15%
Excavated Soils	25%	36%	48%
Steel	6%	8%	10%
Concrete	6%	7%	9%
Mortar	7%	10%	12%
Bricks	7%	9%	11%
Concrete Blocks	7%	10%	13%
Plastics	3%	4%	5%
Ceramics	6%	9.5%	12%
Chemicals	2%	2.5%	3%
Minerals	0%	2.5%	5%

Material	Minimum	Average	Maximum
Pre-fabricated Units	1%	5%	8%
Mixed Waste	N/D*	25%	N/D
Marble/Granite	N/D	2%	N/D
Cables, Duct and Pipe	N/D	17.5%	N/D
Corner Bead	N/D	1%	N/D
Glass	N/D	0.5%	N/D
HVAC Insulation	N/D	4%	N/D

** N/D means No data as participants just provide an average number without min and max.*

There are some works and practices that have been conducted regarding the Recycled Concrete Aggregate worldwide; however, these practices are still limited when we talk about the construction industry in Egypt. The major problem that should be raised concerns the question of: Why the use of recycled concrete aggregate is still limited in Egypt and why are contractors and consultants still not encouraged to adopt the Recycled Concrete Aggregate notion even in small construction jobs? The answer to this question is simply the absence of the codes of practices, field experiences, and the know-how issue. Moreover, the environmental and economic aspects concerning the recycled concrete aggregate are still vague and unavailable.

1.3 Objectives of the Study

The objectives of this study are to address the problem and present the professional solutions and guidance for the best utilization of recycled concrete aggregate.

Through this study, the researcher is aiming to:

- To present the development of the concept of concrete recycling and the *past experiences* worldwide in terms of case studies for projects and studies that have applied recycled concrete aggregate.

- To present the *know-how* of recycling concrete in terms of the production process, the layout of production plants, the crushing mechanisms applied and the types of crushers used.
- To present the *properties and quality* of recycled concrete aggregate in terms of the previous experiments and field tests performed by various scientists worldwide.
- To present and analyze the *environmental and economic concerns* regarding the recycling of construction and demolition waste concrete and to present a *management plan* for recycling concrete that can act as guidance for investors.
- To develop an *economic model* that would assess the national savings that could result from recycling construction and demolition waste concrete to produce recycled aggregate and also evaluate the viability of creating markets for recycled concrete aggregate.
- To propose *specification limits* for some of the properties of recycled concrete aggregate in order to assist in developing a code of practice for using recycled concrete aggregate in the Egyptian construction industry.

1.4 Methodology

The afore-mentioned objectives are achieved through subsequent stages:

First: Conduct literature review concerning the concept and development of recycled concrete aggregate (RCA) in order to be used as a source of aggregate and also present the past experiences worldwide in this field through case studies for projects that have applied the concept.

Second: Consult selected sectors of the Egyptian construction industry using a surveying questionnaire.

The questionnaire would be covering general information about the firms surveyed, the nature of the services offered, the volume of yearly work, the types of projects constructed, construction waste amounts, how do they deal with the wastes (if applicable), and their ideas about the Recycled Concrete Aggregate (RCA). The questionnaire is developed parallel to and based on the literature review mentioned in stage 1. The sectors to be surveyed will include, but not limited to, the following:

- Demolition contractors.
- Ready-mix concrete batch plants.
- Greater Cairo Districts Authorities (Local Municipalities).

Third: Investigate and present the know-how of concrete recycling in terms of tackling the production process, layout of recycling plants, crushing mechanisms applied and types of crushers.

Fourth: Present and analyze the previously performed laboratory and field tests by various scientists worldwide in order to determine the properties and quality of recycled concrete aggregate.

Fifth: Define the environmental and economic concerns for recycling and present a management plan for recycling the construction and demolition waste.

Sixth: Analyze the data gathered from previous stages in order to develop a preliminary economic model to assess the national savings that could result from recycling construction and demolition waste concrete to produce recycled aggregate and also evaluate the viability of creating markets for recycled concrete aggregate and also to propose provisional guidelines for the recycled concrete aggregate application in Egypt in terms of specification limits for some of its properties.

1.5 Contents and Organization

The study is composed of seven chapters. The first chapter introduces the thesis topic with an overview on the situation in Egypt. The problem statement is presented followed by the main objectives and a brief methodology.

A detailed coverage of the historical background of the concept of recycled concrete aggregate and its development in the construction literature are tackled in chapter two. The chapter presents case studies for projects that have applied the concept in order to present the past experiences in this field and to differentiate between the various terminologies of recycled concrete aggregate.

Chapter three is a field research on the awareness of the selected sectors in the Egyptian construction industry regarding the concept of recycled concrete aggregate and construction waste management. And chapter four is devoted for presenting the know-how of recycling concrete in terms of production process, layout of recycling plants, crushing mechanisms applied and type of crushers used. Also it presents the performance of the material in terms of quality, mechanical properties, durability and testing methods and the results achieved by various scientists worldwide. Although chapter four is considered to be a continuation of the literature review, yet the author intended to place it after chapter three as it provides the know and properties of the material which are the first reasons for the lack of the concept application in Egypt.

Chapter five discusses the environmental and economic concerns involved in recycling and presents a management plan.

Chapter six develops an economic model and proposes specification limits for some properties of the recycled concrete aggregate in order to develop provisional guidelines for the implementation of the concept of recycled concrete aggregate. The last chapter presents a summary and conclusions of the work performed and provide recommendations for future research.

The following flowchart summarizes the problem to be tackled and the methodology that shall be followed in order to reach the objectives of the study.

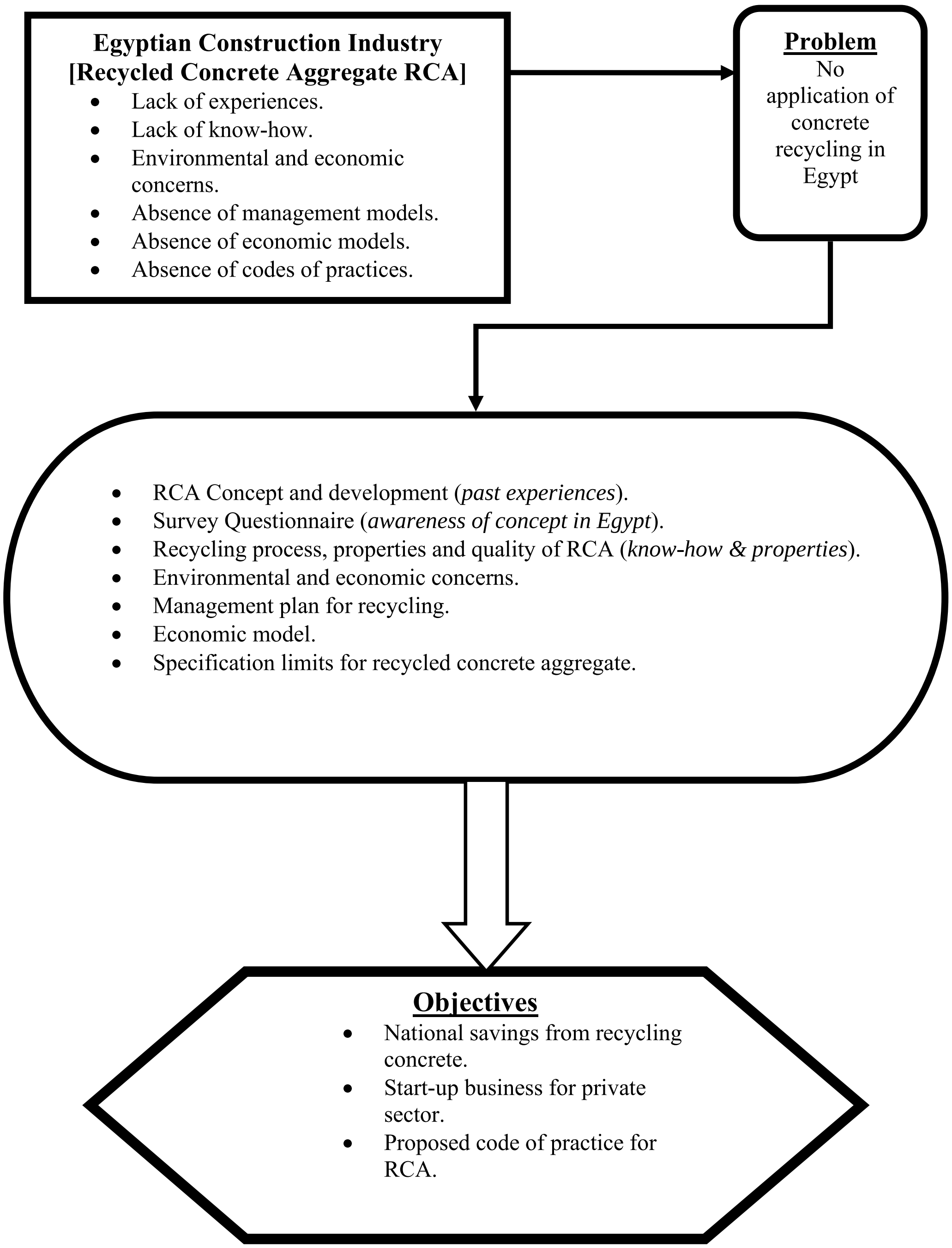


FIGURE 1.2: STUDY FLOW-CHART

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The use of recycled concrete aggregate has become more essential. The technique seems to have found more application in the USA and Europe as it is becoming increasingly difficult and expensive for demolition contractors to dispose of building waste and demolition rubble. Also this technique assists in protecting the natural resources and eliminates the need for disposal by using readily available concrete as an aggregate source for new concrete.

Recycling and re-use of building rubble present interesting possibilities for economizing on waste disposal sites and conserving natural resources. RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures) Technical Committee 37-DRC has contributed to the elimination of existing technical barriers and promotion of the use of mineral materials from building rubble (Hansen, 1992).

The purpose of this chapter is to present a historical background about the progress of the researches that have been conducted worldwide regarding the recycling of construction materials and a focus will be given more on to the concrete aggregates. The researches discussed in this chapter are addressed relatively to the period they were produced. Starting from the end of the Second World War in 1945 till the beginning of the new millennium, there were major researches, papers and studies that tackled the concept of recycled concrete aggregate.

Moreover, the chapter aims to make the construction industry and public authorities in Egypt aware of the past experiences that have been encountered in various countries all over the world for recycling of concrete through presenting case studies and experiences of the world on the subject, much of which has not been easily accessible before.

2.2 Historical Review and Development of Concrete Recycling Concept

"Concrete" (Opus Caementitium) buildings made with crushed brick have been known since Roman times (Hansen, 1992). The concrete channels of Eifel water supply to Cologne are an example of this type of structure in which the binder is a mixture of lime and brick-dust. Crushed brick concrete with Portland cement was used in Germany from 1860 for the manufacture of concrete products. Systematic investigations on the effect of the cement content, water content and grading of crushed brick have been carried out since 1928. However, the first significant applications only date back to the use of rubble "debris" from buildings destroyed in the Second World War (Schulz, 1985; Hendricks, 1985).

During the period of reconstruction after the Second World War, it was necessary on the one hand to satisfy an enormous demand for building materials and on the other to remove the rubble from the destroyed cities. The amount of brick rubble in German towns was about 400 to 600 million cubic meters (Schulz, 1985). Using this rubble made it possible not only to reduce site clearing costs but also to contribute considerably for fulfilling the need for building materials. Rubble-recycling plants in the Federal Republic of Germany produced about 11.5 million cubic meters of crushed brick aggregate by the end of 1955, with which 175,000 dwelling units were built (Schulz, 1985).

The statistics compiled by the Association of German Cities showed that by the end of 1956, about 85% of all building rubble in the German Federal Republic had been cleared. In two-thirds of all municipalities clearance was complete at the beginning of 1957. Only in 15 large cities did about a million of cubic meters still remain by the end of 1955 (Schulz, 1985). By about 1960, there was no longer any rubble recycling done in the Federal Republic. There are many technical and economical directives and guidelines dating from the period of 1945 and 1960 (the main one being DIN 4163 (Schulz, 1985)) and also many publications. The German Society for the Use of Rubble issued a total of 437 publications.

In the UK also, rubble was used recycled and used after the Second World War, although to a lesser extent than in Germany. It applied more particularly to redundant defense structures, mainly to brick masonry constructions. These were very seldom rendered so that there was hardly any presence of impurities as would be the case with other types of construction.

2.2.1 First State-of-the-Art Report 1945-1977

The first state-of-the-art report on recycled concrete as an aggregate for concrete was prepared by Nixon, on behalf of RILEM Technical Committee, covering the period 1945-1977. In his review, Nixon concluded that a number of workers have examined the basic properties of concrete in which the aggregate is the product of crushing another concrete. Most have concentrated on uncontaminated material, often old laboratory test specimens (Nixon, 1978). There was a good agreement on most aspects of the behavior of such recycled concrete.

The most marked difference in the physical properties of the recycled concrete aggregate was higher water absorption, and it seemed likely that this was due to absorption by cement paste adhering to the old aggregate particles. There was a general agreement that the compressive strength is somewhat lower compared with control mixes, but there did not seem to be any correlation between the loss in strength and the water-cement ratio of the final concrete. There was only limited evidence (and some disagreement) on the effect of the strength of the original concrete on the strength of the new concrete made with it as aggregate, but it seemed probable, that when the concrete failed, it was the adhering mortar on the crushed concrete aggregate that was the weakest link. The use of crushed concrete fines did not seem to have any great effect on the compressive strength of the concrete, but it seemed to reduce the workability significantly. When only crushed concrete coarse aggregate was used, the workability was little different from control mixes. Again, when using recycled coarse aggregate, there was little difference in the modulus of elasticity; there was no information on the effect of fines on this property (Nixon, 1978).

The durability of the recycled concrete was examined mostly with respect to the freeze/thaw resistance of the concrete, and the results suggested that with uncontaminated concrete there was no problem. In fact with concrete containing a highly porous frost aggregate there might actually be an improvement probably because the cement paste blocked up the pores. Drying shrinkage had been found to be somewhat greater in the recycled concrete. There was no information on creep, wetting expansion or resistance to aggressive solutions such as sulfates of recycled concrete (Nixon, 1978). Less work had been carried out on the effect of impurities in the crushed concrete on the properties of the final concrete. Most of which had been done had been devoted to sulfate impurities originating from gypsum plaster.

In 1977 Nixon concluded his report by saying (Hansen, 1992):

"*There seems to be a reasonable knowledge of the basis engineering properties of the recycled concrete, and the main penalty in its use is a slightly lower compressive strength compared with a control mix made with the same original aggregate. A more thorough investigation of the effect of the strength of the original concrete would seem to be needed, however, and also a fundamental investigation of the mode of failure of the recycled concrete which may enable the reason for the lowered strength to be understood and counteracted. The main field in which more information on the behavior of the recycled concrete is required is its durability. Creep, wetting expansion and porosity all need to be examined as does the effect of aggressive solutions*".

2.2.2 Second and Third State-of-the-Art Reports 1978-1989

The second report on recycled aggregates and recycled aggregate concrete was prepared by Hansen and published in Materials and Structures Vol. 19, No 111, May-June 1986, pp. 201-246, covering developments between 1978 and 1985. The third report was an updated version of the second report including developments in the period of 1985-1989. More than 80 new publications have been reviewed (Hansen, 1992).

In its scope, the report was limited to review developments to 1989 concerning the use of crushed concrete as recycled aggregates for production of new, plain and reinforced normal weight concrete in building and roads construction. By crushed, concrete was meant concrete made with Portland cements, Portland pozzolan cements or blast furnace slag cements, and with natural or manufactured sand or a combination thereof and with aggregates consisting of natural gravel, crushed gravel, crushed stone, air-cooled blast furnace slag or combination thereof. Crushed concretes made with high-alumina cements or with light weight aggregate, brick-waste aggregate, or aggregates made from other waste products were not dealt with in this report. Crushed concretes, which contained more than 5% of other substances, were also excluded from this review (Hansen, 1992). The report revealed some of the important properties of the recycled concrete aggregate and the properties of the resulting recycled aggregate concrete during the period in which the report was prepared.

2.3 Past Experiences in the Field of Concrete Recycling

2.3.1 The UK Experience with Recycled Demolition and Construction Wastes

The UK aggregates industry has faced growing opposition from a wide spectrum of society who were dissatisfied with the ever increasing demands for extraction sites; sites which were often situated in heavily populated or very attractive parts of the country. In addressing these concerns, the Department of the Environment commissioned research into two potential alternative sources of aggregates. Firstly, the importation to the areas of greatest demand of aggregates from remote coastal super-quarries in Norway, Scotland and possibly northern Spain. Secondly, the use of recycled construction wastes. In his paper "Occurrence and Utilization of Mineral and Construction Wastes" in 1991, Andrew Marsay has reported on the research into the scope for utilizing the various mineral waste sources as recycled aggregates (Whitbread, Marsay, & Tunnell, 1991).

Environmental Constraints

The pressures of urban development, which is a major consumer of aggregates, conflicted with the pressures to conserve the countryside and minimize the environmental disturbance of quarrying activities. The regional pattern of surplus and deficit resulted in quite substantial inter-regional flows of materials. The south-east of the UK as well as the west midlands and the north-west regions were major deficit regions which imported from elsewhere while the south-west, east-midlands and north Wales were the principal exporters. The solution to the deficit problem had been to mobilize traditional sources of supply of aggregates and to transport them over considerable distances. The traditional sources of supply were, of course, sand and gravel, crushed rock and marine dredged aggregate; but the impact of long-distance transportation had been felt mainly in the supply of crushed rock where economies of scale of production had conducted to the emergence of inland super-quarries which, coupled with productivity improvements on the rail network, had led to quarry-to-railhead distribution systems (Whitbread, Marsay & Tunnell, 1991).

There appeared to be limits, however, to the extent to which established sources of supply could expand to meet the growing deficits of the regions containing major cities. Environmental pressures at the major sources of crushed rock supply suggested that expansion might be more problematic in the future. These environmental pressures and the growing local deficits in aggregates supply had encouraged the search for alternative sources of materials through the recycling of mineral and construction wastes to produce secondary aggregates.

The Role of Recycled or Secondary Aggregates

The potential environmental gains to be realized from the use of recycling had been recognized for some time. For example, in 1972, the Government of the UK introduced a "dual tendering procedure" that was designed to give greater opportunities for the use of mineral wastes as road fill where such materials were available (Rainbow, 1994). In the 1976, the Verney Report, "Aggregates the Way Ahead", sought to encourage greater utilization of mineral wastes as aggregates by recommending a procedure whereby a full cost benefit analysis would be undertaken of different sources of imported fill including secondary materials. Moreover, the Department of Environment's Mineral Planning Guidance Note 6 of 1989 stated:

"*Increased utilization of wastes could reduce the demand for primary aggregates with benefits of avoiding the dereliction caused by tipping at the same time as reducing the land for extracting natural aggregates*" (Rainbow, 1994).

Nevertheless, policies which would have brought environmental costs directly into the decision making calculations of the building and construction industries and which would have altered the balance of materials use in favor of secondary materials have been limited in their scope and the intensity of their application till 1990. The government White Paper in 1990, "This common Inheritance" was the beginning. This White Paper reported the intention on the part of the government to address some of the environmental problems associated with the waste management practices prevailed at that time. The White Paper contained proposals which would raise the price of landfill to levels that would reflect more accurately the scarcity of the land which might have an effect on the disposal patterns of mineral wastes such as demolition rubble and might make recycling more viable (Rainbow, 1994). It further indicated the government's readiness to consider new policy initiatives to internalize environmental costs and purse the "polluter pays" principle.

It was against this policy context that in early 1990 the Department of the Environment commissioned research from ARUP Economics & Planning into the role of secondary aggregates (Whitbread, Marsay, & Tunnell, 1991). The main objectives were to:

- Assess current stockpiles and utilization of mineral wastes.
- Identify technical and economic constraints on greater use of mineral wastes.
- Recommend policy measures to increase the take-up of secondary aggregates.
- Establish a framework for environmental evaluation of policy.

At that time, the research found that a total utilization of aggregates of about 332 million tonnes per annum at the end of the 1980s decade in Great Britain, about 32 million tonnes per annum were derived from secondary materials. Although the research has revealed few estimates for various types of mineral wastes such as: China Clay Waste, Colliery Spoil Waste, Slate Waste, Power Stations Ashes Waste, and Blast-furnace and Steel Slags Waste, our main analysis will be focused on the construction wastes as it is the major concern of the study.

In 1990, it was reported that there were about 24 million tonnes of demolition and construction waste arising per annum in Great Britain and the methods of disposal relied very largely on the costs to the demolition contractors (Whitbread, Marsay & Tunnell, 1991). The material was often hauled to landfill sites but the requirements to produce a level building site meant that a large proportion of masonry and concrete arisings could be used as fill.

Economic and Environmental Policy Appraisal

For most secondary materials the principal disadvantage associated with further use was the transport costs from source to the principal areas of market deficiency. There were other difficulties to be overcome, including customer acceptance of the product and the need to maintain necessary standards of safety and performance. The research of the UK Department of Environment in 1990 identified a number of actions that government could take to assist with greater utilization of the secondary materials (Rainbow, 1994). Many of the immediate environmental impacts resulting from the extraction of primary aggregates applied equally to the utilization of secondary materials. This was due to the similarity between the processes, namely the extraction from an appropriate source, processing often involves noise, dust and visual intrusion, and transportation to market, often using Lorries. However, there were longer term environmental gains which favored the utilization of waste resources for aggregate. There were:

- The avoidance of the permanent loss of land-related amenity which occurs when aggregates are extracted, for which satisfactory restoration and aftercare can never fully compensate. Similarly, when the wastes are tipped there is also a loss either of land-related amenities or of landfill space which could be saved if more recycling took place.
- The beneficial use of an otherwise wasted material.

The research concluded that a package of policy measures would be required to secure maximum use of the secondary materials, but potentially the most effective and direct measures that could be applied were those that would alter the relative prices of primary and secondary aggregates in favor of secondaries (Rainbow, 1994). One method, suggested at that time, of altering relative prices was a tax or industry-administered levy on primary aggregates and in the following analysis the implications of different levels of tax/levy were followed through. The objective was to provide a means of addressing the question: how much would the environmental benefits be worth? The following paragraphs will address the analysis for the implications of the different levels of tax/levy recommended by the UK Department of Environment research in 1990.

On the basis of a total aggregate demand in the UK in 1989/90 of about 332 million tonnes per annum, it was estimated that relative price changes resulting from different levels of tax or levy would bring forth the supply response shown in table 2.1 (Rainbow, 1994). This assumed that the substitution of secondary for primary aggregates would be the only consequence of the tax/levy. An increase in price might perhaps dampen overall aggregates demand, but this effect was excluded and, for the present purposes of showing the implications of substitution, would not significantly effect the conclusions.

Table 2.1: Effect of Price Changes on Secondary Aggregate Demand in the UK, (Rainbow, 1994)

Price Change %	0	15	30	50
Total Demand (mtpa)*	332	332	332	332
Total Sec. Aggs Demand (mtpa)*	32	42	55	80
Marginal Sec. Aggs. Demand (mtpa)*	---	10	23	48

** mtpa: million tonnes per annum (year).*

In economic terms, the costs of such a policy are the additional resources required to produce the increased output of secondary aggregates instead of the substituted primary aggregates. So the economic cost is the cost of the secondary materials less the cost of producing the equivalent amount of primary materials, which is shown in figure 2.1. The triangular area between points A and B shows the additional resource cost involved in producing the same total output of aggregates with a tax or levy in place.

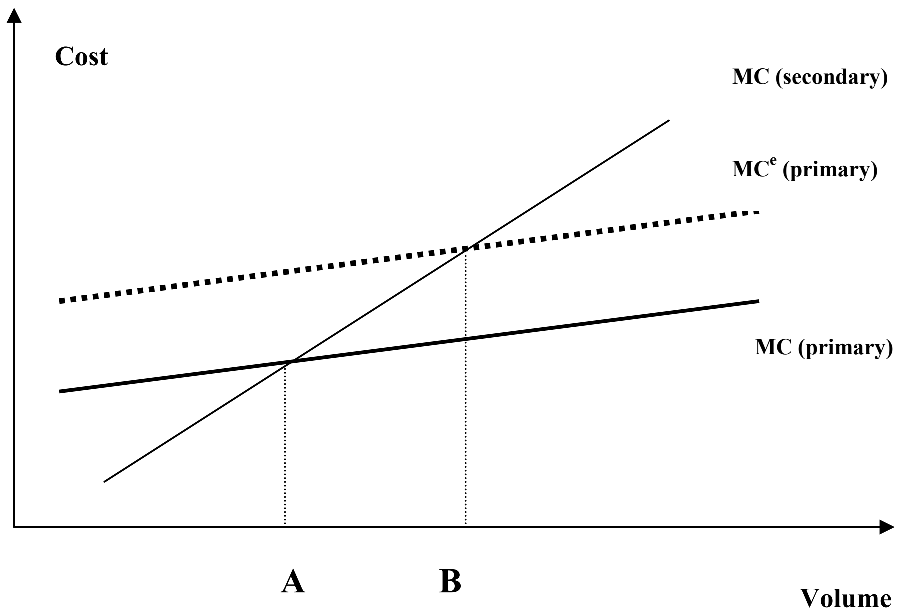


FIGURE 2.1: RESOURCE COST OF APPLYING AN ENVIRONMENTAL TAX OR LEVY TO PRIMARY AGGREGATES, (RAINBOW, 1994)

Notes: *MC = Marginal Cost of Supply, Direct Costs only.*
MC^e = Marginal Cost of Supply, including environmental costs.

When assuming an average production cost for aggregates of £5.00/tonne, the economic cost of the measure would be calculated as shown in table 2.2 (Rainbow, 1994).

Table 2.2: The Economic Cost of a Tax/Levy on Primary Aggregates in UK, (Rainbow, 1994)

Price Change %	15	30	50
Additional Sec. Aggs. (mtpa)	10	23	48
Marginal addition (mtpa)	10	13	25
Additional resource cost (£m)	3.75	17.25	60.00
Marginal resource cost (£m)	3.75	13.50	42.75

**mtpa: million tonnes per annum.*

The additional economic or resource cost given by the triangular area between points A and B in figure 2.1, was calculated approximately as:

[Half of the product of the tax rate, the price of primaries and the additional volume of secondary aggregate utilization]; for example:

(15% x £5.00 x 10 mtpa)/2 = £3.75 m.

The additional resource cost of moving from one level of policy intensity to the next is shown in the last row of table 2.2 as the marginal cost of the policy. The rationale for incurring the above resource cost would be the environmental benefits from land that would otherwise be used for primary quarrying and waste tipping. Table 2.3 shows the area of lands that would be saved. The calculation assumed that 10 ha of land was saved for every million tonnes of primary aggregates substituted by secondaries and 1.25 ha for every million tonnes of waste disposal avoided (Rainbow, 1994).

Table 2.3: Annual Land Saving Arising from Greater Use of Secondary Aggregates in the UK, (Rainbow, 1994)

Price Change %	15	30	50
Quarrying land saved (hectares)	100	230	480
Tipping land saved (hectares)	13	30	60
Total land saved (hectares)	113	260	540
Marginal land saved (hectares)	113	147	280

From these estimates of land area saved, and the resource costs of the policy intervention, it was possible to assess the cost per hectare which was the (minimum) valuation of the land that would be necessary to justify the policy. This is shown in table 2.4.The findings of the policy and the research were that the higher the tax or levy imposed on the industry producing the primary aggregates, the higher the implied valuation of each hectare of land that was saved. The implied environmental values of the land saved were between £30,000 to £150,000 per hectare (at the time of research) when expressed in marginal cost terms (Rainbow, 1994). These values (less any allowance for continuity of existing uses such as agriculture) could be viewed as the price of preserving environmental amenity associated with non-quarrying uses of the land. If a tax or levy on primary aggregates production was introduced, it would probably be regarded publicly as an environmental tax even if it were not explicitly linked to the imputed environmental gain. Such a tax or levy would probably achieve greater overall impact and be more compelling if at the same time, grants were made available for restoration and/or for supporting investment in the recycling process.

Table 2.4: Imputed Values per hectare of Land Saving Arising from Greater Use of Secondary Aggregates in the UK, (Rainbow, 1994)

Price Change %	15	30	50
Marginal land area (ha)*	113	147	280
Marginal resource cost of policy (£m)	3.75	13.50	42.75
Imputed marginal value/ha (£,000)	30	90	150

** ha: hectares.*

The Appraisal of Recycling the UK Roads

Another important research that tackled the use of recycled secondary aggregates instead of primary or virgin aggregates was addressed by A.D. Gill and Woodward in 1994. The paper considers the potential for using recycling as a viable option in highway construction in the United Kingdom. The basic construction and material requirements are outlined. The sources of materials are then discussed followed by the factors which need to be considered if recycling is to see future growth in the roads construction (Rainbow, 1994).

The Layered Structure of a Road

The structure of a road is made up of a number of layers. Aggregates are required at all levels but both the quality and the cost of the materials used generally increases from the bottom towards the top. This means that specification requirements for the wearing course or topmost layer are considerably greater than for the bottom capping and sub-base layers. By building in layers, a very wide range of constructional materials can be used. From a practical point this relates to reductions in cost if abundant local low quality materials can be used to provide the large amount required for the lower layers. Although the quantity of materials is less with higher layers their total costs may be higher as they may have to be transported considerably distances should suitable local supplies not exist.

For each layer, different specification requirements are needed as the different layers perform different functions. This ranges from the ability to withstand the polishing and attrition caused by trafficking to the distribution of stresses in the lower layers, i.e. it is a case of "horses for courses" (Rainbow, 1994). In this context, it would be very attractive should secondary and other types of recycled materials be shown to perform to the same standard as traditional sources now in use.

Factors to Consider about Recycling

Although it is possible to say that there are many hundred's of millions of tonnes of potentially recyclable material available, the fact of its existence does not automatically warrant their use in a highway's construction. Other factors need to be taken into account before what is perceived as the environmentally acceptable alternatives of recycling is adopted by the industry, some of these factors are the location of the material source, the transportation costs from the source to the market, the traditional experience and the know-how, the long term performance of the material and its durability and the modern environmental pressures.

Uses of Recycled Materials in Highway Construction

There are two main uses of recycled materials in the highway's construction:

- Capping and sub-base materials: as the specification requirements for these materials are quite low, there is a great potential market for such recycled materials, either on their own or in contribution with primary materials such as virgin crushed rock aggregate.
- Road-base and surfacing materials: as the specification requirements for these layers are much higher, this necessitates the raw recycled material to possess a higher level of performance. Candidates for this type of use are surfacing planings which should contain a relatively high quality aggregate. However, unsound aggregate is a problem that must be considered.

Road-Base and Surfacing Recycling Process

The use of recycling in these layers usually, but not always, requires the material to be bound with bitumen or cement. It is possible to categorize the different types of recycling process as used for road-base and surfacing layers as follows:

- Hot-mix/off-site
- Cold-mix/off-site
- Shallow hot-mix/in-situ
- Shallow cold-mix/in-situ
- Deep cold-mix/in-situ

Generally, in terms of cost, the in-situ processes are to be favored as they do not require extra transport, handling and processing. Each of these process types will now be defined and discussed. The potential of each will also be given.

Hot-Mix/Off-Site Processes

This is the traditional type of recycling. In this process, existing materials are removed by planing, transported to a hot-mix plant and then reprocessed with virgin aggregates and bitumen to comply with the specification requirements for hot-mix materials such as Hot Rolled Asphalt. Gill and Woodward stated in their paper "A Critical Appraisal of Recycling the UK Roads" that this method was used in the

Northern Ireland by the Department of Environment Roads Service for a number of motorway and dual carriageway re-surfacing contracts. The first was in 1988 on the M1 motorway and involved the use of Hot Rolled Asphalt planings applied to virgin aggregate and bitumen. It was found out that the recycling mixing process required careful control to provide a satisfactory end-product. Initial trials proved that mixes containing up to 50% recycled material could be used successfully (Rainbow, 1994).

Cold-Mix/Off-Site Processes

This is similar to hot-mix/off-site in that it involves recycling at a central plant. The exception is that the process involves the use of cold mixing with either one or a combination of foamed bitumen, bitumen emulsion, cement and lime.

Shallow Hot-Mix/In-Situ Processes

This may be termed as a surface re-generation process for existing wearing course materials such as Hot Rolled Asphalt.

The process first involves heating the roads surface layer, scarifying followed by reshaping and then reinforced by a thin overlay of new asphalt. Typically this is 20-25 mm thick and is heat welded to the old material. The total depth of treatment is about 50 mm with cost savings of 15-20% as claimed by Gill and Woodward. Examples of this type of process include that known as "Repave". Due to the size of the plant involved, this process has tended to be restricted to major roads. But as trunk roads and motorways account for only about 4% of the UK's total road network, the processes potential expansion must be restricted. However, the process is showing favor in Europe (Rainbow, 1994).

Shallow Cold-Mix/In-Situ Processes

This process, commonly known as "Retread", has been in service since the Second World War in the UK. It was originally introduced as a relatively cheap method of repairing badly damaged roads during the war. The fact that this process has survived as long is testimony to its value within the road maintenance industry in the UK.

Retread involved firstly the scarifying and reshaping of an existing road or footway surface. Once completed, virgin aggregate may be added to re-profile the road surface; alternatively excess aggregate may be removed. After the desired profile has been achieved, bitumen emulsion is applied using a spray tanker. This is harrowed into the full 75 mm depth of the retread layer to ensure an even mix. This is then followed by compaction of the layer. Finally, a surface dressing is applied using between 3 mm to 14 mm chippings to give adequate texture depth to the surface. Depending upon the type of emulsion used in the final dressing, and if the site is to be subsequently overlaid, a further surface dressing may be required in 9-12 months to finally seal the surface.

This method of in-situ cold recycling is appropriate for the rejuvenation or reshaping of residential and generally lightly roads.

The retread process has been shown to be a cost effective alternative to planing out and adding a new overlay; giving a claimed cost saving of between 25-35% as stated by Gill and Woodward (Rainbow, 1994). As it uses a "cold emulsion" it also has the advantage of being attractive from both a Health and Safety viewpoint as well as to the environment.

In-Depth Cold-Mix/In-Situ Processes

As the name applies, this process treats the road to a far greater depth than does the shallow cold-mix/in-situ process. This type of process can recycle an existing road surface to a depth ranging from 150 mm to 300 mm. This process involves pulverizing the existing road surface to a depth of up to 300 mm. This material is then compacted and reshaped. Excess material is removed at this stage. Once the desired profile has been achieved the material is rotovated again, during which time bitumen emulsion, foamed bitumen and/or cement will be added in pre-determined quantities and thoroughly mixed throughout the layer.

Again the layer is compacted and shaped before being sealed with sprayed bitumen emulsion and sealing grit. Typically this layer is then overlain with some other material to provide a new running surface. As well as an enhanced speed of operation the in-depth recycling process typically offers a cost saving of up to 40% and an energy saving of up to 10% when compared to traditional methods, since the existing road is being used as a horizontal quarry (Rainbow, 1994). Its principal advantage is that it is very flexible depending upon what is being recycled. Due to its significant financial and environmental benefits, and the pressure placed upon the local authorities in the UK, this type of process would have potential in the future. According to a research performed at the University of Ulster, this material was capable of out-performing "virgin" material.

2.3.2 The Use of Recycled Aggregates in the USA Roads

The use of recycled aggregate in roads construction has been widely used in the United States. The American Concrete Institute has performed various field tests regarding the use of recycled aggregate. The main field in which recycled aggregate was applied is the construction of roads.

Construction materials are increasingly judged by their ecological characteristics (ACI Committee 555, 2001). The recycling of concrete is a relatively simple process. It involves breaking, removing, and crushing existing concrete into a material with a specified size and quality. According to the ACI Committee 555 report in 2001, the quality of concrete with recycled concrete aggregates is very dependent on the quality of the recycled material used. Reinforcing steel and other embedded items, if any, must be removed, and care must be taken to prevent contamination by other materials, such as: asphalt, soil, chlorides, glass, gypsum board, sealants, paper, plaster, wood and roofing materials which can be troublesome.

The crushing characteristics of hardened concrete are similar to those of natural rock and are not significantly affected by the grade or quality of the original concrete (ACI Committee 555, 2001). Recycled aggregates produced from all but the poorest quality original concrete can be expected to pass the same tests required of conventional aggregates. In general, applications of recycled concrete aggregate, without any processing, include: many types of general bulk fills, bank protection, base or fill for drainage structures, roads construction and embankments. After removal of contaminants through selective demolition, screening, and/or air separation and size reduction in a crusher to aggregate sizes, crushed concrete can be used as:

1. New concrete for pavements, shoulders, median barriers, sidewalks, curbs and gutters, and bridge foundations.
2. Structural grade concrete.
3. Soil-cement pavement bases.
4. Bituminous concrete.

Recycled concrete can be batched, mixed, transported, placed and compacted in the same manner as conventional concrete. Special care is necessary when using recycled concrete aggregate. Only up to 10% to 20% recycled fine aggregate is beneficial. The aggregate should be tested at several substitution rates to determine the optimal rate (ACI Committee 555, 2001). It is generally accepted that when natural sand is used, up to 30% of natural crushed coarse aggregate can be replaced with coarse recycled aggregate without significantly affecting any of the mechanical properties of the concrete. Replacing higher amounts will result in increased drying shrinkage, while strength and freeze-thaw resistance are not significantly affected. Often recycled aggregate is combined with virgin aggregate when used in new concrete. An example of a mix design using concrete aggregates in a pavement application is shown in the following table prepared by the ECCO, Recycling Concrete and Masonry, 1999 (ACI Committee 555, 2001).

Table 2.5: Examples of Mix Designs for Recycled Concrete Pavements, (ACI Committee 555, 2001)

Concrete Ingredients	Minnesota DOT* (Kg/m^3)	Wisconsin DOT* (Kg/m^3)	Grand Forks, ND Int'l Airport (Kg/m^3)	Wyoming DOT* (Kg/m^3)
Cement (Type I)	280	285	237	290
Fly Ash (Type C)	49	65	77	79
Water	151	157	136	153
Recycled CA	967	1,077	979	800
Natural CA	---	---	---	357
Recycled FA	---	---	---	150
Natural FA	712	780	748	523
Admixtures: Air Entrained Water Reducer	 Yes No	 Yes No	 Yes Yes	 Yes Yes

** DOT: Department of Transportation.*

2.3.3 The German Experience

The experience of Germany regarding the application of recycled concrete aggregate is addressed in the form of a case study for a building project that was built in the last century. The project is called the "WALDSPIRALE" building.

Introduction to the "WALDSPIRALE" Project

The second building project in Germany made from concrete with recycled aggregate, the "Waldspirale" by Friedensreich Hundertwasser, was built in Darmstadt, from November 1998 up to September 1999. The first building project with recycled aggregate was the office building "Vilbeler Weg" in Darmstadt (RÜHL, 1997).

Summary of the "WALDSPIRALE" Project

For the production process a consistency controlled method was developed and implemented. Numerous tests during concrete production covering both freshly mixed and hardened concrete properties were evaluated. The results in chapter 4 show that the consistency controlled method is applicable for concrete with recycled aggregate and leads to concrete of equal quality compared to concrete made from natural dense aggregate (RÜHL, 1997).

Because the concrete mixtures used vary in terms of the amount of recycled aggregate used, an extensive testing was necessary before construction. In these tests the development of rigidity was measured and an initial consistency was fixed for each mixture. This initial consistency was the value to be reached by every concrete mixture in the concrete mixing plant. The optimization process was a big challenge for the personnel involved. The consistency of the concrete was monitored visually and using the so-called 'consistency-meter' of the mixing plant. Additionally, the consistency was measured after mixing using the flow table test (RÜHL, 1997).

For the first building project with recycled aggregate, the office building "Vilbeler Weg" in Darmstadt, the amount of water added in concrete production was constant which led to a variable workability due to variant weather conditions, unsheltered storage of all aggregate fractions and therefore different aggregate surface and core moisture. The standard deviation of the compressive strength was between 3.01 N/mm^2 and 4.23 N/mm^2 (RÜHL, 1997).

2.3.4 The Experience of Hong Kong

The experience of Hong Kong regarding the application of recycled concrete aggregate is addressed in the form of a case study for a park project that was built in this century. The project is called the "WETLAND PARK".

Introduction to the "Wetland Park"

Hong Kong Wetland Park is located at the north-western part of Hong Kong and is close to the border between Hong Kong and Shenzhen of the Mainland. After completion in 2005, the park has a 10,000 m^2 visitor center comprising exhibition galleries, AV theatres, souvenir shops, cafes, children play areas, classrooms and a resources center. In the project, recycled aggregate is employed to replace part of the virgin aggregate in the majority of the structural concrete. The highest concrete grade used is C35. The designed slump is 100 mm but in some cases, 75-mm slump concrete is also used. The concreting work of the Phase II project started in April 2003 and up to September 2003, a total volume of about 5,000 m^3 of ready mixed concrete using recycled aggregates has been placed (Hong Kong Polytechnic University, 2006).

The Recycling Industry in Hong Kong

The construction activities in Hong Kong generate about 14 million tons of construction and demolition (C&D) materials each year (Hong Kong Polytechnic University, 2006). Recycling the C&D materials is one of the measures to reduce the burden on public fill capacities in Hong Kong. The rapid development of Hong Kong in the last two decades led to the generation of huge volumes of construction and demolition materials. In the past, the inert portions of C&D materials, such as rock, concrete and soil, had been beneficially reused as fill materials in forming land for Hong Kong's development. However, the increasing opposition to sea reclamation by the general public has rendered most reclamation projects either delayed or much reduced in scale. If these materials have to be disposed of at landfills, it will accelerate the depletion of the already limited precious landfill spaces. Hong Kong is now facing a crisis on how to accommodate these surplus materials. Apart from putting more efforts in minimizing its generation and the setting up of temporary fill banks, recycling is one of the most effective means to alleviate the growing problem.

In mid July 2002, the Hong Kong SAR government established a pilot C&D materials recycling facility in TUEN MUN to produce recycled aggregates for use in government projects and for research and development works. The plant has a designed handling capacity of 2,400 tons per day (Hong Kong Polytechnic University, 2006). The processing procedure for recycled aggregate comprises the following processes: (1) a vibrating feeder/grizzly for sorting the hard portions from the inert C&D materials which are suitable for subsequent recycling; (2) a jaw crusher (primary crusher) for reducing the sorted materials to sizes of 200 mm or smaller which can be handled by the secondary crushers; (3) a magnetic separator, manual picking gallery and air separator for removal of impurities before the materials are fed into the secondary crusher; (4) cone crushers (secondary crusher) for processing the clean materials into sizes smaller than 40 mm; (5) vibratory screens for separating the crushed recycled aggregates into different sizes; and (6) storage compartment for temporary storage for recycled aggregates. The facility is able to produce Grade 200 rock-fill and recycled aggregates of various sizes, ranging from 40-, 20-, and 10-mm coarse aggregates to fine aggregates (<5 mm) for different applications.

Due to the varying sources of the incoming materials, a prudent quality control approach has been adopted by the recycling plant. Only suitable materials (e.g., crushed rocks, concrete) are processed at the plant. Brick and tiles are generally not allowed. The produced recycled aggregates are sampled and tested daily. Since production commenced in July 2003, the facility has already produced approximately 240,000 tons of recycled aggregates with consistent high quality that meets the specification requirements (Hong Kong Polytechnic University, 2006).

<u>Specifications and Applications for the "WETLAND PARK"</u>

Internationally, the RILEM specification is the most commonly accepted standard for recycled aggregates. But in Hong Kong, due to their limited experience in using recycled aggregates and Hong Kong's different nature of building construction, a more prudent approach has been adopted. After detailed laboratory investigations and plant trials, the government has formulated two sets of specifications governing the use of recycled aggregates for concrete production (Hong Kong Polytechnic University, 2006).

For lower grade applications, concrete with 100% recycled coarse aggregate is allowed. Recycled fines are not allowed to be used in concrete. The target strength is specified at 20 MPa and the concrete can be used in benches, stools, planter walls, concrete mass walls and other minor concrete structures. The specification requirements for recycled aggregate are listed in Table 2.6.

Table 2.6: Specifications Requirements for Recycled Aggregate for Concrete Production in Hong-Kong, (Hong Kong Polytechnic University, 2006)

Requirements	Limit	Test Method
Min dry particle density (kg/m^3)	2,000	BS 812: Part 2
Max water absorption (%)	10%	BS 812: Part 12
Max content of wood & other material less dense than water (%)	0.5%	Manual sorting in accordance with BRE Digest 43
Max content of foreign materials (e.g. metals, plastics, clay lumps, asphalt, glass, etc) (%)	1%	Manual sorting in accordance with BRE Digest 43
Max fines (%)	4%	BS 812: Section 103.1
Max content of sand (< 4 mm) (%)	5%	BS 812: Section 103.1
Max content of sulfates (%)	1%	BS 812: Part 118
Flakiness Index (%)	40%	BS 812: Section 105.1
10% fines value (kN)	100 kN	BS 812: Part 111
Grading	Table 3 of BS 882:1992	---
Max chloride content (%)	Table 7 of BS 882 – 0.5% by mass of chloride ion of combined aggregate	---

For higher grade applications (up to C35 concrete), the current specifications allow a maximum of 20% replacement of virgin coarse aggregates by recycled aggregates and the concrete can be used for general concrete applications except in water retaining structures.

As of the end of October 2003, there have been over 10 projects registered to consume over 22,700 m^3 of concrete from Grades 10 to 35 using recycled aggregates. The usage varies from reinforced pile caps, ground slabs, beams and parameter walls, external building and retaining walls, to mass concrete (Hong Kong Polytechnic University, 2006).

2.4 Terminologies for Recycled Concrete

It is of great essence to present and define the various terminologies used in this industry. Based on a Japanese proposed standard (Hansen, 1992) on "Recycled aggregate and recycled aggregate concrete" which was prepared by the Building Contractors Society of Japan in 1977, the following terminologies were suggested:

2.4.1 Waste Concrete

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.

2.4.2 Conventional Concrete

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

2.4.3 Original Concrete

Concrete from reinforced concrete structures, plain concrete structures or pre-cast concrete units which can be used as raw material for production of recycled aggregates (or for other useful purposes).

2.4.4 Recycled Aggregate Concrete

Concrete produced using recycled aggregates or combinations of recycled aggregates and other aggregates.

2.4.5 Original Mortar

Hardened mixture of cement, water and conventional fine aggregate less that 4-5 mm in original concrete. Some original mortar is always attached to particles of original aggregate in recycled aggregates.

2.4.6 Original, Conventional, Virgin or Primary Aggregates

Conventional aggregates from which original concrete is produced. Original aggregates are natural or manufactured, coarse or fine aggregates commonly used for production of conventional concrete.

2.4.7 Recycled Concrete Aggregates or Secondary Aggregates

Aggregates produced by the crushing of original concrete; such aggregates can be fine or coarse recycled aggregate.

CHAPTER 3
RECYCLED CONCRETE AGGREGATE IN THE EGYPTIAN CONSTRUCTION INDURSTRY

3.1 Introduction

Research data are used to assist in tracking the performance and measure success at achieving objects. According to Carl McDaniel and Gates, surveys have a rate of usage in research compared to other means of collecting primary data (McDaniel & Gates, 1998). This is attributed to the fact that surveys provide the researcher with answers for the need to know why, who and how the practice is being carried.

This chapter presents a survey questionnaire (Appendix A) that was designed for four selected sectors of the construction market in Egypt. The selected sectors are the ones involved with the handling of concrete and demolition of structures. The answers were analyzed to express the response of the selected sectors in terms of both the construction waste management in Egypt and the concept of recycling concrete rubble so as to be used as an aggregate for new concrete. The main objectives of the questionnaire are:

a) Identify the intensity of utilizing Recycled Concrete Aggregate concept in the construction industry.
b) Discover the main obstacles that hinder the use of Recycled Concrete Aggregate concept.
c) Propose idea for eliminating these obstacles.
d) Present ways to enhance the application of Recycled Concrete Aggregate.

The chapter starts with a brief description of the questionnaire, its organization and structure. A description of the type of companies and authorities participating in the questionnaire along with the reasons for why they were chosen is then offered. A summary of the collected information is summed up with some interpretations from the applicant's responses and analysis.

3.2 Survey Questionnaire

3.2.1 Questionnaire Organization

Many researches, papers, studies and articles use questionnaires as a tool of measurement. Sometimes the surveyor needs to assess the extent to which a specific phenomenon exists, while in other times, he needs to measure the knowledge of the population about a certain topic. The type and format of the questionnaire differs with the objectives of the surveyor. The format of the questionnaire at hand is deemed to be a closed-ended questions questionnaire. A closed-end question is the one that requires the respondent to make a selection from a list of responses. The main advantage of closed-ended question is simply the avoidance of many of the problems of the open-ended questions such as lies in the interpretation-processing area (McDaniel & Gates, 1998).

The questionnaire was developed to be short and to the point that would not be affecting the type nor the quantity of the required data. The survey was divided into thirteen questions. The first question was used to collect some general information about the applicant's firm. The second and third questions capture the knowledge and awareness of the applicant with respect to the concept of Recycled Concrete Aggregate. The fourth question allocates the codes of practices used in Egypt. The fifth, sixth and seventh questions identify the major sources of the RCA and quantities being adopted. The eighth question determines the problems that are encountered in conducting and adopting the RCA concept. The ninth and tenth questions were devoted for the types of contracts and the value of projects under which the applicant can use the RCA concept. The eleventh question tackles the crushing mechanisms recommended. The twelfth question discusses the factors that affect the decision of adopting the RCA concept. And finally the last question deduces from the respondents a case study when his/her firm has adopted the RCA concept.

3.2.2 Data Collection

The questionnaire was addressed to a sample of forty-four selected companies, consultants, private contractors, owners and domestic authorities working in various types of construction projects in Egypt. The selected sample was chosen to selectively represent the sector of the construction industry that would adopt or be aware of the RCA concept. The involved applicants' are small, medium and large scale companies and were selected to represent the spectrum of parties participating in a given construction related project as shown in table 3.1. These applicants represent a combination of Consulting and Design Firms (CD), Project Management Firms (PM), Construction Firms (C), Ready-Mix Concrete Plants (RM), Demolition Contractors (DC), Investors (Owner) and local authorities (LA).

The participant groups were presented in this format so that each group will resemble at least one stage of the construction project life. The owners group represents the project pre-construction phase and the operation phase. The consulting group partially participates in the pre-design phase, mainly in the design phase, and partially in the construction phase. The contractors group participates during the project construction phase. The project management group provides the construction management during the construction phase. The ready-mix concrete plants group provides the concrete during the construction process. The Demolition Contractors group becomes involved when the owner wishes to remove the whole structure or part of it. And finally, the local authorities are involved when it comes to codes and specifications. This way, all the project phases are covered by the questionnaire.

To ensure that the survey is covering various sizes of companies; whether small or medium or large scale companies, a criterion discussing the annual work volume of the company was addressed in the questionnaire. For small scale companies, the annual work volume would be considered as a minimum of 100,000 Egyptian Pounds. For medium scale companies, a minimum of 1,000,000 Egyptian Pounds is determined and for the large scale companies, a minimum of 10,000,000 Egyptian Pounds was presented. For private contractors, demolition contractors, a minimum of 50,000 Egyptian Pounds was addressed.

Although most of the questionnaires were conducted in a personal meeting with the participants, several questionnaires were faxed to companies with an introduction overview of the topic via a phone conversation. A number of international companies that are involved in construction activities in Egypt or participating in any type of Consortium or Joint Venture with an Egyptian firm are represented in the questionnaire.

3.2.3 Survey Questionnaire Results and Analysis

The survey questionnaire results were as follows:

- For *question one* which gathers information about the services offered by the participant's company, 12% of the participants are consulting and design firms, 14% are project management firms, 6% are ready-mix concrete plants, 26% are construction firm and/or contractors, 32% are demolition contractors, 8% represent owners and developers, and 1% represents the local authorities or the municipalities of Greater Cairo. Table 3.1 shows the mentioned results and also Table A.1 (Appendix A) shows the detailed breakdown of the participating firms.

Table 3.1: Classification of Firms Covered by the Questionnaire

Type of Service	CD	PM	RM	C	DC	Owner	LA	Total
Total Participating Firms	6	7	3	13	16	4	1	50
Percentage to Total	12%	14%	6%	26%	32%	8%	2%	100%

Where: CD: Consulting and Design Firms, (PM): Project Management Firms, (RM): Ready-Mix Concrete Plants, (C): Construction Firms, (DC): Demolition Contractors, (OWNER): Investors, (LA): local authorities.

- For *question two* which captures the knowledge and awareness of the applicant with respect to the concept of Recycled Concrete Aggregate, 100% of the consulting and design firms are aware of the concept of concrete recycling, 71% of the project management firms are aware of the concept, 100% of the ready-mix concrete plants are aware of the concept, 77% of the construction firms are aware of the concept, 19% of the demolition contractors have some knowledge about the concept, 50% of the owners are aware of the concept, 0% was recorded for the local authorities. Table 3.2 shows the mentioned results.

Table 3.2: Participants' Awareness of Recycled Concrete Aggregate Concept

Type of Service	CD	PM	RM	C	DC	Owner	LA	Total
Firms Aware of RCA	6	5	3	10	3	2	0	29
Percentage to Total	100%	71%	100%	77%	19%	50%	0%	58%

- For *question three* which records the annual work volume performed by the firm, 83% of the consultants and design firms are large scale firms where its annual volume of work is more than 10,000,000 Egyptian pounds, 84% of the construction firms are large scale companies, and 100% of the investors are large scale sized companies. Table 3.3 shows the results attained from the participants concerning question three. Also Table A.2 in Appendix A shows the breakdown of participating firms in terms of their annual work volume.

Table 3.3: Classification of Participating Companies in terms of Work Volume

Type of Service	CD	PM	RM	C	DC	Owner	LA
Total (L)	5	4	3	11	---	4	N/A
Percentage of (L) to total Firms	83%	57%	100%	84%	0%	100%	N/A
Total (M)	1	2	---	1	---	---	N/A
Percentage of (M) to total Firms	17%	29%	0%	8%	0%	---	N/A
Total (S)	---	1	---	1	16 P	---	N/A
Percentage of (S) to total Firms	0%	14%	0%	8%	100%	---	N/A

* L: Large Scale company (volume: minimum 10M EGP yearly).
* M: Medium Scale company (volume: minimum 1M EGP yearly).
* S: Small Scale company (volume: 100K EGP yearly).
* P: Private contractors and demolition contractors (volume: minimum 50K EGP yearly).
* N/A: Not Applicable.

- For *question four* which captures the knowledge of codes of practices for recycled concrete aggregate, none of the participants had any information about any codes of practices in Egypt.
- For *questions five and six* which ask about the major sources of recycled concrete aggregate, 100% of the participants advised that the waste concrete resulting during construction and from ready-mix batch plants production is the best source of recycled aggregate. However, demolition wastes could be used if wisely controlled.
- For *question seven* which tackles the volume of concrete performed by the participant's company yearly, the total quantity performed by the ready-mix batch plants participated in the survey amounted to 810,000 cubic meters, the construction firms performed a total volume of 66,100 cubic meters, and the demolition and private contractors performed a total volume of 8,000 cubic meters. Table 3.4 shows the results attained and also Table A.3 in Appendix A shows the annual concrete volume performed by each participating firm.

Table 3.4: Volume of Concrete Works Performed by Participating Firms

Type of Service	CD	PM	RM	C	DC	Owner	LA	Total
Annual Volume of Concrete (m^3)	---	---	810	66.1	8	---	---	884.1
Percentage to total	---	---	92%	7%	1%	---	---	100%

* Values of concrete volume are in 1,000 cubic meters.
* Values were provided only by construction firms, ready-mix plants and demolition contractors.

- For *question eight* which captures the problems encountered in the industry of recycling, 64% of the participating firms stated that the lack of experiences, lack of know-how and the environmental and economic concerns are the main problems and/or reasons that hinder the recycling industry of concrete, 62% of the participants mentioned that the lack of management and economic models are major problems. However, 100% of the participants stated that the absence of codes of practices is the main problem. Table 3.5 shows a summary of the results concerning question eight, and table A.4 in Appendix A shows the respond of each participating firm.

Table 3.5: Survey Participants Opinions Regarding the Problems Facing the Recycling of Concrete industry in Egypt

Problem	Percentage out of total 44 firms
Lack of Experiences	64%
Lack of know-how	64%
Absence of Codes of Practices	100%
Environmental and Economic Concerns	64%
Absence of Management and Economic Models	62%

- For *question nine* capturing the effect of the contract type on the recycled concrete aggregate choice when compared to conventional aggregate, 84% of the participating firms have mentioned that the unit price contract would be more acceptable; whereas, 16% have mentioned that the contract type would make no effect on the choice of recycled aggregate when compared to the conventional aggregate. Table 3.6 shows the results attained and table A.5 (Appendix A) shows the respond of each participant.

Table 3.6: Contract Type Effect on Using Recycled Concrete Aggregate

Contract Type	UP	LS	CP	BOOT	BOT
Total	37	---	---	---	---
Percentage to total	84%	---	---	---	---

* UP: Unit Price contract.
* LS: Lump Sum contract.
* CP: Cost Plus contract.
* BOOT: Build, Own, Operate and Transfer contract.
* BOT: Build, Operate and Transfer contract.

- For *question ten* which asks about the size of project the participant would prefer to apply recycled concrete aggregate, all the participants have mentioned that it would be recommended to apply it in small projects since there are no previous experiences available to them.
- For *question eleven* which asks about the crushing mechanisms to be recommended, none of the applicants was aware of the crushing mechanisms of concrete recycling.
- For *question twelve* which captures the factors that would affect the decision of using recycled concrete aggregate in a project, 100% of the participants mentioned that the material properties should conform with the specification limits stated in the Egyptian code and they also mentioned that the price of recycled concrete aggregate per cubic meter should be competitive to the natural aggregate.
- For *question thirteen* which asks for a case study, none of the participants could provide any. Table 3.7 shows that only 8% of the participants have used recycled concrete aggregate.

Table 3.7: Participants Applying Recycled Concrete Aggregate

Type of Service	CD	PM	RM	C	DC	Owner	LA
Total Participating Firms	6	7	3	13	16	4	1
Firms Aware of RCA	6	5	3	10	3	2	0
Percentage to Total	100%	71%	100%	77%	19%	50%	0%
Firms Applying RCA	0	0	0	1	0	0	0
Percentage to Total	0%	0%	0%	8%	0%	0%	0%

3.2.4 Conclusions

Implementation of Recycled Concrete Aggregate Concept

Fifty participants from different specializations representing forty-four companies participated in the questionnaire. Only twenty-nine of them were aware of the RCA concept; however, only one company is adopting the concept of RCA in the manufacturing of pre-cast and pre-stressed concrete pipes. Figure 3.1 shows that only 8% of the participants used recycled concrete aggregate. Most of the participants have mentioned that the lack of codes of practices, specifications, and the absence of economic studies are behind the limited application of the RCA concept in the Egyptian construction industry. Moreover, most of the participants have mentioned that this concept could be acceptable especially in roads construction, pavements construction and other non-residential structures. Figure 3.2 demonstrates the relation between applying RCA and the type of project under consideration. From the figure, it is deduced that RCA is most recommended for roads construction, pavements construction and infrastructures. This large percentage, recommending RCA for roads, pavements and infrastructures, could be attributed to the fact that most of the participants do not prefer to take the risk in such a concept that has no codes or specifications in the market.

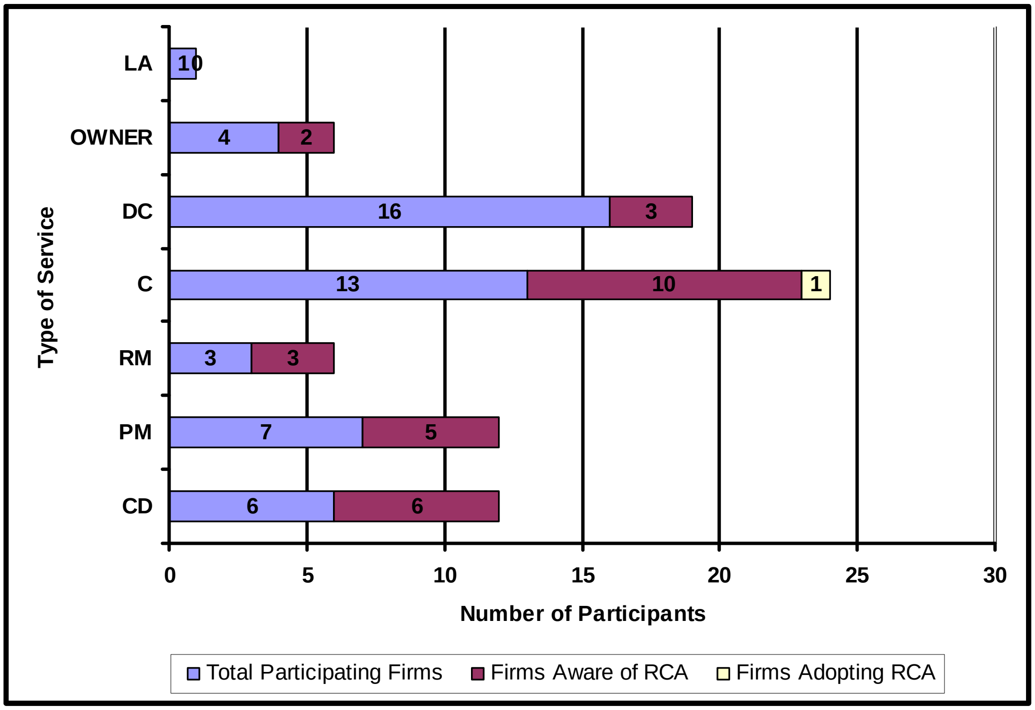


FIGURE 3.1: EGYPTIAN FIRMS AWARE AND/OR ADOPTING RCA

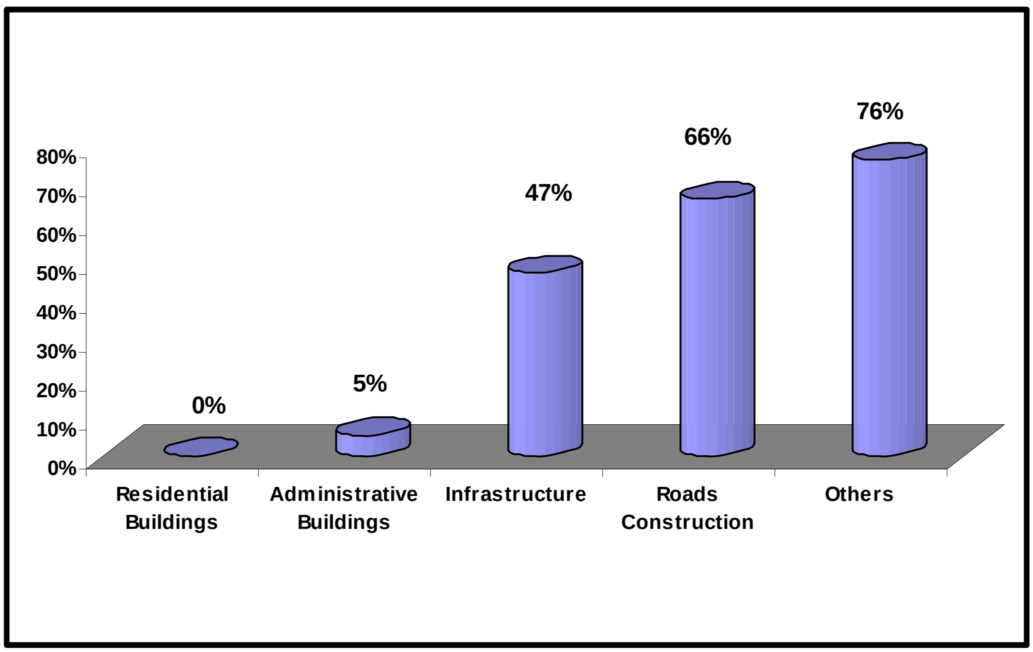


FIGURE 3.2: RELATION BETWEEN ADOPTING RCA AND THE TYPE OF PROJECT UNDER CONSIDERATION

Owners and contractors were the main two groups who were in favor the most of using this concept as it will save a lot of money in terms of cost per meter cube of concrete. Also the type of contract is one of the major items that can influence the application or adoption of the RCA concept. Almost eighty-four percent of the surveyed applicants stated that a "unit price" contract would encourage the application of RCA. In addition, one hundred percent of the participants stated that the major sources of RCA would be waste concrete resulting from construction activities and from ready-mix batch plants. They also noted that the rubble of demolished structures could be another source if wisely controlled. Still the lack of codes, specifications, field experiences and know-how are the main reasons that almost all of the participants considered to be the obstacles that would hinder the application of the concept in the Egyptian construction industry.

Construction Waste Management (CWM) in Cairo: Problems, Barriers and Downsides

Egypt lacks a mechanized system for collecting and disposing of construction and demolition (C&D) waste; as a result, several private contractors are active in this process. When C&D waste is generated on site, recyclable constituents such as metals and plastic materials are separated and sold to recycler contractors. The remnant is handed to hauling contractors who will load, haul, and dispose of the waste materials at once of the allocated landfills in the vicinities of Cairo in return of a hauling/tipping fee. State charges for disposing of C&D waste at landfills are very low, and it is economically beneficial for constructors to landfill their wastes.

Based on the survey undertaken at the local municipalities of Cairo, main problems and barriers facing the proper implementation of CWM practices in Cairo can be classified into four categories of production, processing, collecting and hauling, and land filling C&D waste. The lack of local and national laws, regulations, guides, and instructions concerning CWM are the common problems among all four processes; in addition to that, main problems in each process are identified as presented in the following paragraphs.

Problems and Barriers Associated with Construction Waste Management in Cairo

The main problems, downsides and barriers associated with CWM leading to excessive production of C&D waste in Cairo include, but are not limited to:

- Lack of reliable, real-time data on quantity and composition of C&D waste production in Cairo;
- Lack of preference in constructors to implement CWM practices on construction sites, mainly because of low prices of resources as well as low costs of disposal of C&D waste;
- Inappropriate care of the concepts of CWM in design phase of the projects;
- Weak communication between constructor and supplier in order to procure prefabricated, standard, or modular members and materials, resulting in excessive cutting and fitting wastes;
- Cultural failings and lack of cooperation in implementing CWM concepts and practices.

Problems and Barriers Associated with Construction and Demolition Waste Processing in Cairo

Construction and demolition (C&D) wastes are produced daily on construction sites. Ignoring the reusing and recycling causes to send those wastes to landfills. Other alternatives such as incineration and composting to minimize waste headed to landfills are not also seriously considered. In summary the main problems before the application of C&D waste processing procedures include, but are not limited to:

- Poor level of understanding and expertise of constructors regarding C&D waste processing;

- Lack of tendency to the application of new technologies for recycling C&D waste, as a result of high costs of technology transfer in comparison with low costs of raw materials and land filling;
- Lack of a stable ground for investment in the market of recycling C&D waste, mainly due to fluctuations in production rate of C&D waste.

Problems and Barriers Associated with Collecting and Hauling Construction and Demolition Waste in Cairo

The downsides and barriers before proper collecting and hauling of C&D waste include, but are not limited to:

- Diversity of types and capacities of hauling vehicles that perplexes the practice of surveying, planning, and managing the whole process;
- Use of old and inefficient machinery and hauling units in the process;
- Long distance of landfills from sources of waste production in Cairo.

Problems and Barriers Associated with Disposing of Construction and Demolition Waste at Landfills in Cairo

In this process, current problems and barriers include, but are not limited to:

- Abounding status of landfills in the vicinity of Cairo and lack of appropriate land for new landfills;
- Lack of suitable equipment and facilities in Cairo's landfills for proper disposing.

3.2.5 Summary of Questionnaire Results

In an effort to measure the extent to which the RCA concept is applied in the Egyptian construction industry, a survey was conducted and data were collected from forty-four selected companies and individuals.

It was found out that only twenty-nine of the surveyed participants were aware of the RCA concept. Only one participant applied recycled concrete aggregate. Roads, pavements and infrastructure constructions were the three project types with the highest recommendation for the application of the concept. On the contrary, residential and administrative structures had the lowest rates. It was also concluded that the owners and the contractors are the parties who would be eager to carry out the concept. Moreover, it was found out that there are some problems that face the proper management of construction waste in Egypt, much of them are related to production, processing, collecting and land-filling barriers.

Although the concept has found great application in the USA, Europe and other countries, still the concept is faced with several obstacles in Egypt. The lack of codes of practice, specifications, field experience, know-how and economic feasibilities are always the nuisance for the analyst.

CHAPTER 4
RECYCLING OF CONCRETE - PRODUCTION, QUALITY, PROPERTIES, CODES AND STANDARDS

From the survey results, it was deduced that two of the main reasons behind the absence of the application of concrete recycling in Egypt are the lack of know-how and the absence of information regarding the material properties of recycled concrete aggregate. This chapter aims to present the know-how of concrete recycling in the form of presenting the complete layout of recycling plants, the production process, the applied crushing mechanisms and the types of crushers used. Moreover, the chapter will present the various researches that have tackled the material properties of recycled aggregate.

4.1 Production of Recycled Aggregate

4.1.1 Layout of Production Plants

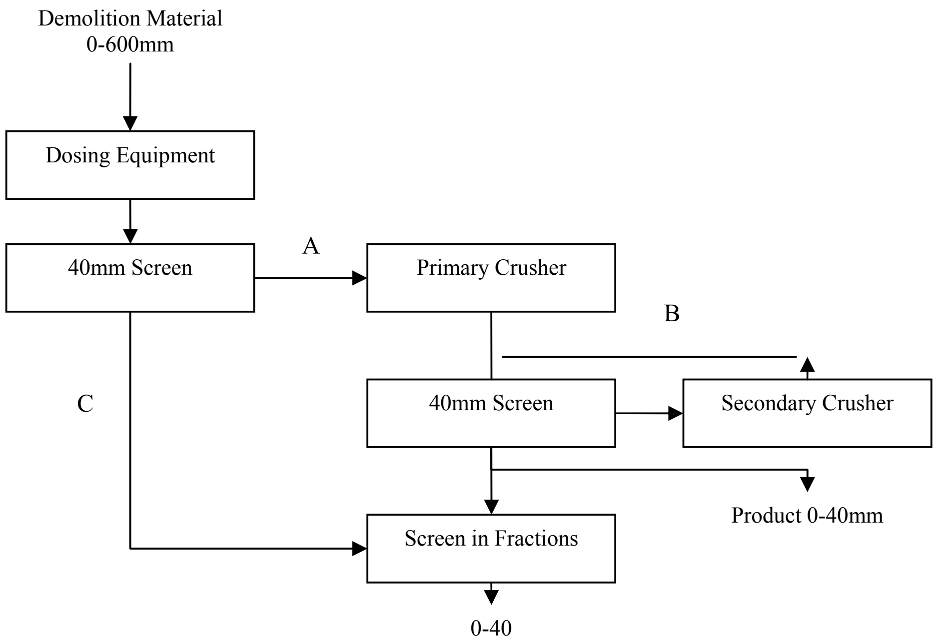
Plants for production of recycled aggregates are not much different from plants for production of crushed aggregate from other sources. They incorporate various types of crushers, screens, transfer equipment, and devices for removal of foreign matters. The basic method of recycling is one of crushing the debris to produce a granular product of a given particle size. The degree of reprocessing carried out after this is determined by the level of contamination of the initial debris and the application for which the recycled material will be used such as: (1) General bulk fill; (2) Base or fill in drainage projects; (3) Sub-base or surface material in road construction or (4) New concrete manufacture.

Boesman (Boesman, 1985) has discussed problems associated with the design of recycling plants for demolition waste. Drees (Drees, 1989) has published a comprehensive review of the lay-out of recycling plants for demolished concrete, their equipment, treatment of raw materials and economy. Hironaka, Cline and Shoemaker

(Hironaka, Cline, & Shoemaker, NCEL-TN-N-1766) studied different aspects of the recycling process of pavement including breakup and removal, steel reinforcement removal, crushing, screening, stockpiling, mix design, testing, placing, finishing and performance. They conclude that recycling of Portland cement concrete 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.

A number of different processes are possible for the crushing and sieving of demolition waste which mainly consists of concrete, such as would be the case for example on a pavement rehabilitation project. Some of these possibilities are illustrated in the block diagrams which are shown in figures 4.1a and 4.1b (Boesman, 1985). Installations working according to the principles of one of these schemes are regarded as first generation processing plants. They are characterized by the fact that there are no facilities for removing contaminants, with the possible exception of a magnet for the separation of reinforcement and other ferrous material. Such plants are frequently used on pavement rehabilitation and recycling projects.

Figure 4.1a illustrates the closed system which is generally recommended. The open system of figure 4.1b is advantageous in one way only, because the capacity is greater than that of the closed system, even though the same basic equipment is used. However, the maximum particle size is less well defined when an open than when a closed system is used, and this can lead to larger variations in the size of the end products, particularly when the input flow varies.



A: 40-600mm, B: 40-200mm, C: 0-40mm

FIGURE 4.1A: FLOW-CHART OF TYPICAL PLANT FOR PRODUCTION OF RECYCLED AGGREGATE FROM CONCRETE DEBRIS WHICH IS FREE FROM FOREIGN MATTER (CLOSED SYSTEM), (BOESMAN, 1985)

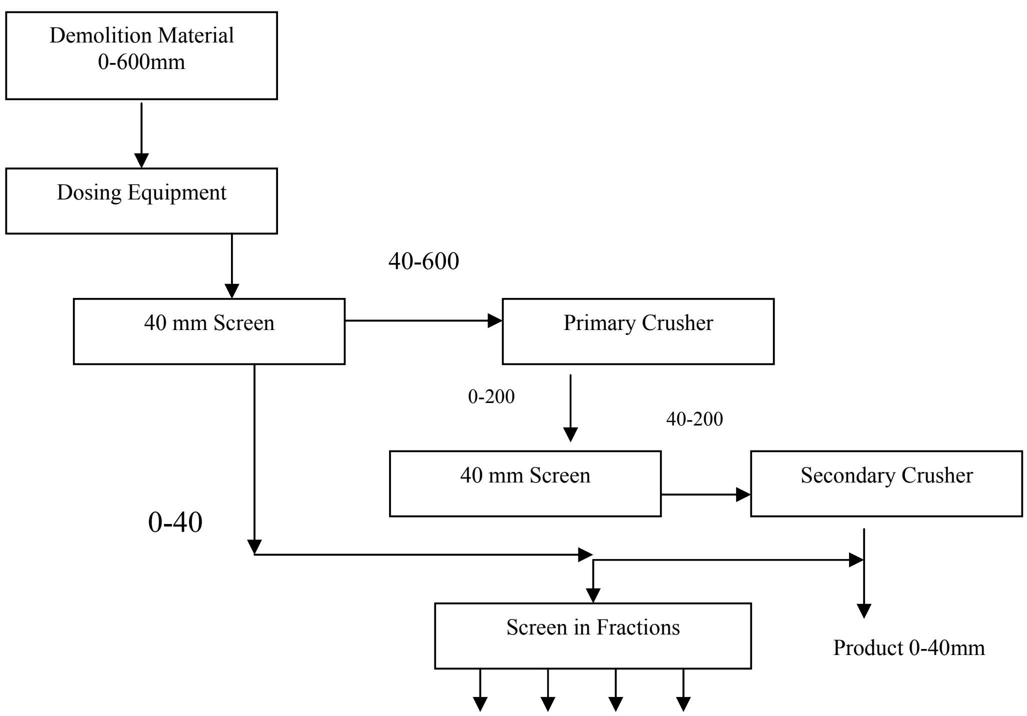


FIGURE 4.1B: FLOW-CHART OF TYPICAL PLANT FOR RE-PRODUCTION OF RECYCLED AGGREGATE FROM CONCRETE DEBRIS WHICH IS FREE FROM FOREIGN MATTER (OPEN SYSTEM), (BOESMAN, 1985)

However, clean concrete cannot always be supplied from demolition site. Demolished concrete often contains foreign matter in the form of metals, wood, hardboard, plastics, cladding, and roof coverings of various kinds. On the basis of first generation plants, the process scheme can be adapted for small amounts of contaminants by removing larger pieces of foreign matter mechanically or manually before crushing, and by cleaning the crushed product by means of dry or wet classification. Installations working according to such principles are regarded as second generation processing plants. Incidentally, a pilot project which was carried out in Denmark (Hartmann & Jakobsen, Private Communication) showed that, when properly organized, manual sorting of demolition rubble on the site and sale of reusable items can be done as economically as plain dumping of demolition rubble.

All second generation plants are similar in basic design, as shown in principle in figure 4.2. Large pieces of debris arriving from demolition sites are typically reduced to 0.4-0.7 m maximum size, for example by means of a wrecking ball and hydraulic shears to cut reinforcement. Large pieces of steel, wood, plastics, and paper are removed by hand. Incoming material is then crushed in a primary crusher which is usually of the jaw or impact type.

Products from the primary crusher are screened on a deck typically consisting of a 10mm scalping screen. Minus 10mm material is wasted in order to eliminate fine contaminants such as dirt and gypsum. Plus 40mm material is passed through a secondary jaw, cone, hammer or impact crusher in order to reduce all products to 40mm maximum size. The 40 – 100 mm material from the primary crusher bypasses the secondary crusher. All material is then washed or air-sifted in order to remove remaining lightweight matter such as wood, paper, and plastics, and the clean product is screened into various size fractions according to customer specifications. All iron and steel is removed by self-cleaning magnets which are placed at one or more critical locations above conveyor belts.

Recycled and processed aggregates which are made from mixed building rubble will usually contain less than 1 percent of impurities, which may be good enough for road construction purposes, but not necessarily acceptable for concrete aggregates. However, when recycled aggregates are made from raw materials which contain more than 95% of old concrete, the end product will usually be clean enough to meet specifications for concrete aggregates without being washed.

In ideal future third generation plants, all demolished material should be supplied to the installation, processed and sold without there being any need to transport large quantities of residual matter to city dumps either from the demolition site or from the processing installation. This would be an ideal situation both from an environmental and an economic point of view. The third generation recycling plants where both rubble and wood wastes are processed are already operating in the Netherlands (Van Eck, 1985).

Bauchard reports that two types of recycling plants operating in France and produce aggregates by primary crushing only, and they employ both primary and secondary crushing. Products from plants that produce aggregates by primary crushing only depend to a large extent on the quality of the demolition material. From an analysis of the products of the four plants which were operating in France in 1987, it may be concluded that the demolition materials in fact are carefully selected. Only plain and reinforced concrete is accepted. This ensures that the quality of the aggregates is adequate for the purposes intended. All four plants utilize impact crushers but from different manufacturers.

Two plants are in operation in France, which produce aggregates by primary and secondary crushing. There are more permanent installations which are designed for the processing of demolition debris of varied origins. However, only one plant makes use of this possibility. It crushes only reinforced and un-reinforced concrete.

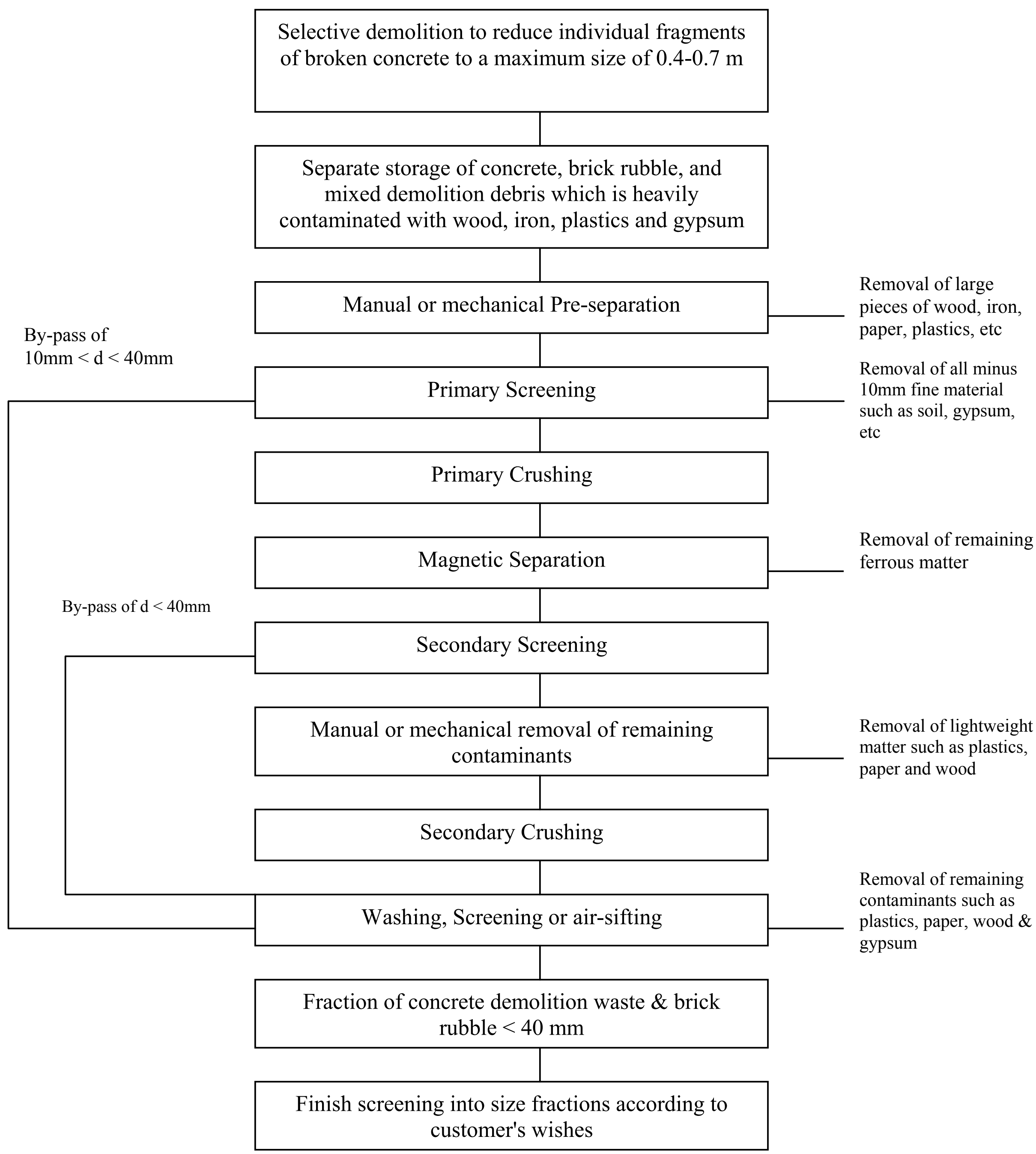


FIGURE 4.2: PROCESSING PROCEDURE FOR BUILDING AND DEMOLITION WASTE
(Hartmann & Jakobsen, 1985)

According to Schulz (Schulz, Ibid. Ref. 135) there are more than 100 recycling plants in Western Germany. Most of these are small with only installations for crushing and screening of pre-selected rubble. Compared with the USA more impact crushers are under in Germany without secondary crushing. These simple plants are not capable of removing contaminants, with the exception of iron and steel by self-cleaning magnets and rubble fines by screening. Only a few larger plants in more populated areas apply washing or air sifting procedures for removal of lightweight particles such as dirt, clay lumps, wood, paper, plastics and textiles, so that frost resistant sub-grade material or base course material can be produced which may justify higher prices.

Trevorrow *et al*. (Trevorrow, Joynes, & Wainwright, 1986) report that a typical site set-up in the UK to produce crusher run material consists of the following items of plant:

1. 360° tracked, hydraulic back-actor.
2. Jaw crusher, single or double toggle.
3. Straight or swing conveyor with screen.
4. Tracked or rubber wheeled loader.

Kabayashi and Kawano report that the Keihan Concrete Company in Kyoto, Japan, has developed a crusher which will remove much of the mortar which remains bonded to crushed concrete aggregate, thus refining the material (Kabayashi & Kawano, 1986). No details are given for what concerns the machine. The paper shows that a higher degree of refining for the recycled aggregate can produce higher quality concrete, but this requires higher manufacturing costs and lower economical efficiency.

4.1.2 Crushers

A number of different crushers such as jaw crushers, impact crushers, hammer mills and cone crushers, were studied in a Dutch investigation (CUR, 1986) in order to determine how well they performed when crushing old concrete. The results can be summarized as follows:

Jaw crushers provide the best grain-size distribution of recycled aggregate for concrete production. The cone crusher is suitable for use as a secondary crusher with 200 mm maximum feed size. Swing hammer mills are seldom used. Impact crushers provide better grain-size distribution of aggregate for road construction purposes, and they are less sensitive to material which cannot be crushed, such as reinforcing bars. The first use of an impact crusher on a pavement rehabilitation project in the US was in Michigan in 1984 (Chase & Lane, 1985). Reinforcement mesh was effectively removed from concrete by means of two revolving magnetized drums after the crusher. When it comes to other properties of recycled concrete aggregate than grain-size distribution, jaw crushers perform better than impact crushers because jaw crushers which are set at 1.2-1.5 times the maximum size of original aggregate will crush only a small proportion of the original aggregate particles in the old concrete.

Impact crushers, on the other hand, will crush old mortar and original aggregate particles alike and thus produce a coarse aggregate of lower quality. Another disadvantage of impact crushers is high wear and tear and therefore relatively high maintenance costs.

All crushers investigated produced approximately the same percentage of cubical particles in recycled aggregates and it appears that the properties of recycled concrete aggregates always are improved by secondary crushing (Kabayashi &

Kawano, 1986; Kaga, Kasai, Takeda, & Kemi, 1986; Kakizaki, Harada, & Motoyasu, 1986; Kasai, Hisaka, & Yanaga, 1986).

A large proportion of the end product less than 40 mm from a crushing and sieving plant comes directly from the primary crusher. This can cause problems if the primary crusher supplies a product which does not satisfy the requirements laid down by the customer. Therefore, it should be possible to adjust the primary crusher so that the ratio between coarse and fine products can be reduced in the end product. This implies that the secondary crusher should have a relatively large capacity.

Economy of coarse aggregate production can be maximized by balancing the crushers. The primary crusher should be set to reduce material to the largest size that will fit the secondary crusher without requiring tertiary crushing.

A similar investigation of crusher efficiencies was carried out by B.C.S.J (B.C.S.J., 1978). Table 4.1 shows that except for grain-size distribution the physical properties of recycled aggregates such as specific gravity, water absorption, sulfate soundness, and Los Angeles abrasion loss percentage were not significantly affected by different types of crushers and crusher settings. The results of this investigation are described in detail by Kakizaki *et al*. (Kakizaki, Harada, & Motoyasu, 1986). Schroeder (Schroeder, 1982) has analyzed removal and reprocessing technologies as they apply to reconstruction of rural highways and airports.

Table 4.1 Physical Properties of Recycled Aggregates Produced by Various Kinds of Crushers, (B.C.S.J., 1978)

Type of Crusher	Type of Concrete	Grain Size of Crusher Product		Specific Density in SSD Condition kg/m3		Water Absorption Percent		Sulphate Soundness Loss Percent by Weight		L.A Abrasion Loss Percent by Weight
		max size, mm	minus 5mm	Fine agg.	Coarse agg.	Fine agg.	Coarse agg.	fine agg.	Coarse agg.	Coarse agg.
Jaw Crusher	w/c = 0.45	25	19.1	2100	2350	11.0	5.8	15.5	58.9	30.5
	w/c = 0.55	25	18.2	2100	2350	11.3	6.2	20.8	48.4	31.0
	w/c = 0.68	25	20.8	2100	2330	11.1	6.4	18.8	60.8	31.2
Horizontal Shredder	unknown	30	33.1	2040	2260	10.5	5.3	12.3	40.9	unknown
Continuous Mill	unknown	25	41.7	2130	2340	8.7	4.6	9.9	29.9	unknown

Results from different countries are difficult to compare because different investigations have been made with different types of original concretes. However, it appears that there is a large difference in percentage of sands produced by different crushers. For the same maximum size of coarse recycled aggregate (25 mm), shredders produced twice as much or 40% of undesirable crusher fines below 4.8 mm, compared with 20% for jaw crushers. It appears that jaw crushers should be used for the processing of plain or lightly reinforced concrete, while heavy impact crushers of various designs appear to be the best choice for normal or heavily reinforced concrete.

If demolition waste is to be recycled, methods of demolition should be used which will reduce individual pieces of debris on the site to a size which will be accepted by the primary crusher in the recycling plant. This is 1,200 mm at most for large stationary plants and not more than 400-700 mm for mobile plants. Thus the recycling of demolition waste requires careful planning on the part of all parties involved in such an enterprise.

4.1.3 Sorting Devices and Screens

In line with specifications for natural aggregate and crushed stone, recycled aggregate is required to be free from dirt, clay lumps, gypsum (from plaster), asphalt, wood, paper, plastics, paint, textiles, lightweight concrete, and other impurities.

The first stage at which demolition debris can be sorted is during the demolition process itself. Thus, if given the incentive the demolition contractor can, by the use of selective demolition methods, recover much of the material from a site in a relatively clean and uncontaminated form. In most cases, such orderly demolition procedures are not viable given the confines of an urban demolition site and the realities of time-penalty clauses (Hansen, 1992). As a result, selective demolition is only carried out where both conditions and time allow and the operation has clear financial advantages. It is significant that demolition contracts involving the dismantling of structures consisting of only one type of material, such as a concrete runway, are highly sought after, since they provide an excellent source of clean debris requiring the minimum amount of processing. Once the demolition has been completed and the debris taken to the recycling plant, opportunities for sorting the debris are confined to selective stockpiling and primary screening.

Selective stockpiling is simply the storing of incoming material in separate stockpiles according to its type and degree of contamination. This gives the plant operator the opportunity of dealing with oversize and undersize material separately. In addition, by building up a sufficient stockpile of a single clean material it becomes viable to optimize the crusher set-up for that material and crush it in a single run. Such stockpiling is only practical on site with sufficient space. A desirable minimum area is one hectare (Lindsell & Mulheron, 1985).

In most recycling plants, larger objects such as pieces of metal sheeting, wooden boards and beams, pieces of asphalt, loose reinforcing bars, and sheets of paper, cloth, and plastics are removed by hand before primary crushing of the debris. After primary crushing, dirt, gypsum, plaster, and other fine impurities are eliminated by passing the crushed materials over a set of scalping screens and wasting all material below 10 mm. Self-cleaning magnets, which are positioned in various patterns of strategic locations over conveyor belts, effectively separate bits of reinforcing bars and other pieces of iron and steel from the stream of crushed aggregate (Hansen, 1992).

Simple dry sieving only separates on basis of differences in size and form. It can only be used successfully to separate material crushed with a jaw crusher, because an impact crusher will crush in a non-selective manner. According to Japanese study

(B.C.S.J., 1978); coarse materials are separated more effectively by inclined screens vibrating at low frequencies and large amplitudes, whilst horizontal screens vibrating at high frequencies and small amplitude are more effective in separating fine material. Dutch results (Boesman, 1985) indicate that for separating lightweight material, adapted flat sieves are the best, giving little loss of the stony material whilst removing some 80% of the wood. Nix (Hansen, 1992) reports that most lightweight matter can be removed from crushed building debris and the aggregate brought to specifications by wet classification. Heimsoth (Hansen, 1992) claims that the same can be achieved by dry processing when impurities are heavier than water.

In principle, fine-grained and lightweight contaminants can be removed from rubble by air classification processes. The most frequently used of these techniques is dry-sifting, a process which can be carried out both vertically and horizontally. An important condition for obtaining a sufficient degree of separation is that the crushed product material must be divided into fractions. This implies that when the material is of a size between 0 and 40 mm, four or five sieved fractions must be obtained; each of which is sifted separately, then remixed. It is a distinct disadvantage that dry-sifting produces an excess of dust which must be controlled.

Alternatively, lightweight contaminants can be separated from heavier bulk by the use of directly applied water jets in combination with a float-sink technique. The so-called 'Aqua-motor' is based on this principle. It is produced by UBA/BMFT in Germany (Hansen, 1992).

By the application of wet classification techniques, wood, hardboard, plastics, straw, and roofing filler as well as suspended sulfates and asbestos fibers can be effectively removed from the size range of 10-40 mm. Sieving on a 10 mm screen prior to washing is recommended, because the 0-10 mm fraction produces large quantities of undesirable sludge in the washing water.

Drees has provided a review of the various methods available for sorting of crushed demolition debris (Drees, 1989). Efficiency of various types was studied by B.C.S.J (*Bulletin of the Chemical Society of Japan*). It was suggested by BCSJ that it should be possible to separate most brick rubble and other deleterious particles from recycled aggregate in a heavy medium of 1950 kg/m^3. In principle, such a technique would allow the processing of highly contaminated and mixed demolition debris to produce clean and well graded aggregates (Hansen, 1992).

4.1.4 Grading of Crusher Products

Table 4.2 shows a typical grading of the total output of recycled aggregate from a laboratory jaw crusher which was set at an opening of 25 mm with the jaws in a closed position (Hansen & Narud, 1983). The crusher was fed three original concretes of different qualities in the form of old 15 x 30 cm test cylinders which had been split in halves. For all practical purposes the overall gradings of the crusher products are independent of the concrete quality in the entire range of water-cement ratios from 0.40 to 1.20.

Table 4.2: Overall Grading of Crusher Products, (Hansen & Narud, 1983)

Size Fraction in mm	Measured Weight Percent of Total Crusher Product			Estimated Weight Percent of Total Crushed Product According to Figure 4.4
	H w/c = 0.40	M w/c = 0.70	L w/c = 1.20	
> 30	3.0	4.2	3.2	0
30-20	27.4	31.9	27.6	32
20-10	35.9	33.2	33.5	34
10-5	14.7	13.4	13.2	17
< 5	19.1	17.3	22.5	17

It is generally assumed that natural rock when fed to a crusher will break according to a 'straight-line distribution' (Anon, 1976-1977) where 15% of the crusher product will be of a size above the crusher setting as shown in figure 4.3.

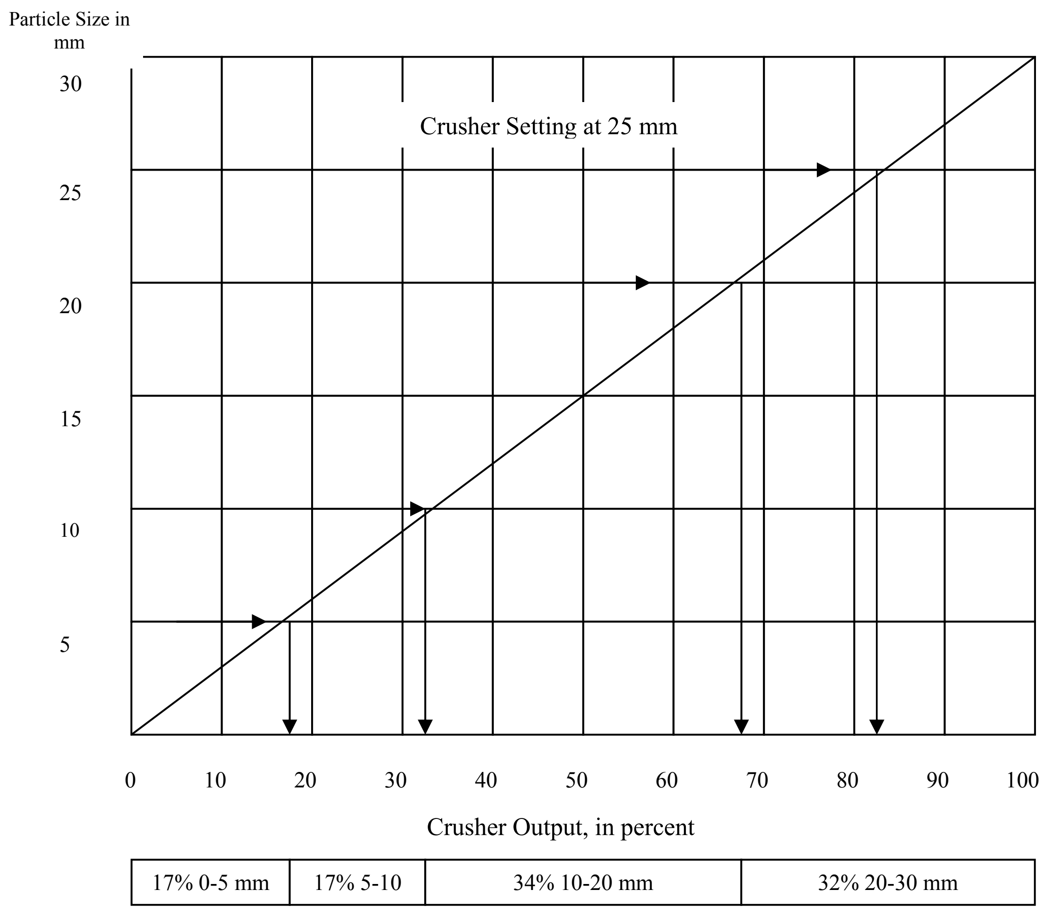


FIGURE 4.3: CORRELATIONS BETWEEN CRUSHER SETTING AND PARTICLE SIZE DISTRIBUTION OF CRUSHER, (ANON, 1976-1977)

Table 4.3: Overall Grading of Crusher Products, Experimental Data, (Hansen, 1992)

Size of Agg. (mm)	Measured Weight Percent of Total Crusher Products	Estimated Weight Percent of Total Crusher Product According to Figure 4.3
> 38	3	3
38	29	34
25	15	15
19	19	19
12.5	8	6
9.6	13	12
4.8	13	11

It is seen from table 4.2 that the actual particle size distributions of crushed concretes are in reasonably good agreement with the predictions that can be made on the basis of figure 4.3. Similar results have been obtained by Fergus (Hansen, 1992) as shown in table 4.3. Usually the grain-size distributions of crusher outputs approximate Fuller curves. Thus, it may be concluded that the crushing characteristics of hardened concrete are similar to those of natural rocks and not significantly affected by the grade of original concrete.

Japanese studies which have been reported by B.C.S.J (B.C.S.J., 1978) confirm that approximately 20% by weight of fine recycled aggregate below 5 mm is produced when old concrete is crushed in a jaw crusher with an opening of 33 mm, also independent of concrete quality (see table 4.1). With jaw openings of 60, 80, and 120 mm, corresponding percentages of fine recycled aggregate produced were 14.1%, 10.6%, and 7.0%. With a jaw opening of 20 mm, Ravindrarajah and Tam found the quantities of fine material below 5 mm to be 23.1, 25.7 and 26.5% by weight for 37 MPa, 30 MPa, and 22 MPa concretes, respectively (Ravindrarajah & Tam, 1985).

In order to be cohesive and workable, fresh concrete requires between 25 and 40% of fine aggregate by weight of total aggregate, depending on the type of sand and its fineness, concrete consistency, water-cement ratio, and maximum size of coarse aggregate. Thus, it may be concluded that by crushing of old concrete in one pass through a jaw crusher there is not enough fine recycled aggregate generated to produce new concrete of good quality when the maximum size of crusher output is between 32 and 38 mm (Hansen, 1992).

The normal procedure in the American practice is to proportion fresh recycled aggregate concrete mixes so that coarse and fine recycled aggregate may be consumed in the same ratio that they are produced. However, due to the fact that insufficient quantities fine recycled aggregate is produced by jaw crusher in order to make new concrete of good workability, it is necessary to add a certain amount of conventional fine aggregate.

At a recycling project in Iowa, the USA (Hansen, 1992) it was found out that optimum finishing properties and workability of fresh recycled aggregate concrete was obtained when 25% of natural sand was mixed with 75% of fine recycled aggregate in a standard pavement mixture which contained a 50-50 mixture of fine and coarse aggregate of 38 mm (1 1/2 inches) maximum size.

It is of interest that the recycling of an existing pavement will produce a total of about 50% more recycled aggregate that is needed to produce the quantity of new concrete which is required to replace the same section with a pavement of equal thickness (Hansen, 1992). However, for reasons of durability, it may not be advisable to use fine recycled aggregate less than 2-3 mm for production of new concrete. However, even if all fine recycled aggregate below 5 mm is rejected it is likely that more than enough coarse recycled aggregate will be produced to replace the same section with a pavement of equal thickness.

Dutch investigations have developed a concept which they called 'Crusher Characteristics' as a useful tool for control of the crushing and sieving processes of old concrete. Crusher Characteristics are graphic representations of the relations between a so-called 'reduction factor, R' and the sieve residues of the crusher output on various size sieves. The reduction factor, R, is defined as *'the ratio between the particle size of crusher input and crusher output for same weight percentage of residue on a given size sieve'* (Hansen, 1992). Different types of crushers yield different crusher characteristics. If for a specific plant the crusher characteristics are known, the grading of the crusher output can be forecast when the grading of the crusher input is known. The use of crusher characteristics can best be shown by means of a numerical example as follows. Hansen (1992) stated that:

"*In order to determine the crusher characteristics for a given impact crusher, the particle distributions of crusher input and output must be determined. For the fragmentation of concrete demolition waste in a specific impact crusher, these are plotted in one and the same graph as shown in figure 4.4. In our example, the reduction factor, R, for a sieve residue of 35% equals 59.5 mm grain size of the crusher input, divided by 9.9 mm grain size of the crusher output, or* R_{35} *= 59.5/9.9 = 6.0*".

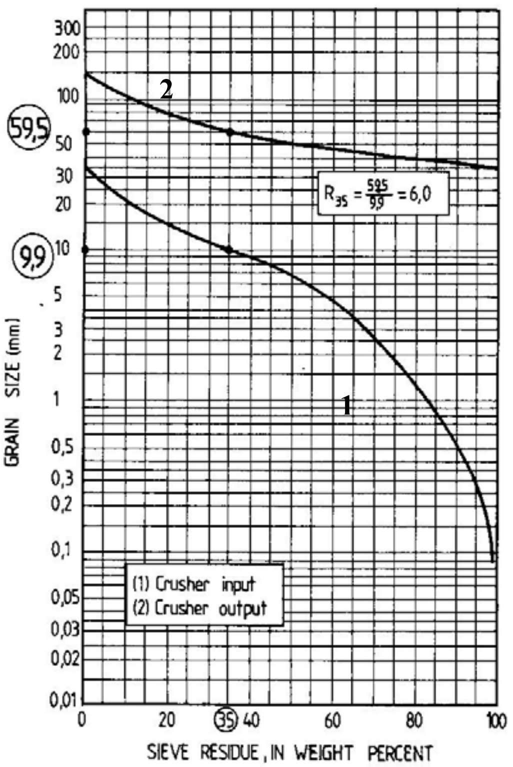


FIGURE 4.4: GRAIN SIZE DISTRIBUTION OF CRUSHER INPUT AND OUTPUT FOR DETERMINATION OF CRUSHER CHARACTERISTICS OF IMPACTED CRUSHER, (HANSEN, 1992)

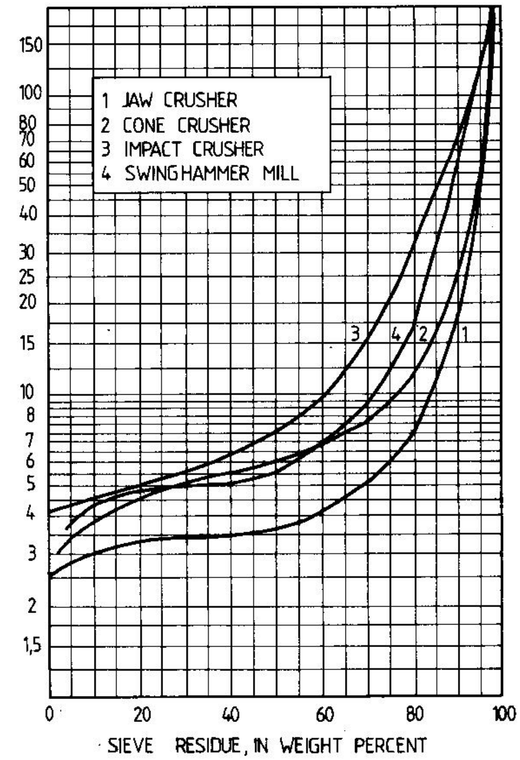


FIGURE 4.5: CRUSHER CHARACTERISTICS, (HANSEN, 1992)

By calculating the reduction factor R for a number of sieve residues and plotting them in another graph with the reduction factor along the ordinate and sieve residue along the abscissa, the crusher characteristic (labeled 3) is obtained as shown in figure 4.5 for the impact crusher that was used in the numerical example. For purposes of a comparison, typical examples of crusher characteristics are also shown in figure 4.5 for a jaw crusher, labeled 1, a cone crusher, labeled 2, and a swing crusher, labeled 4. It is seen from figure 4.5 that impact crushers and swing-hammer mills which both affect crushing by means of different kinds of impact, have greater reduction factors than jaw or cone crushers, which affect crushing by the application of pressure only.

4.1.5 Storage and Handling of Recycled Aggregates

The Japanese proposed standard for the 'use of recycled aggregate and recycled aggregate concrete' (B.C.S.J., 1977) includes the following recommendations for storage and handling of recycled aggregates:

1. Recycled aggregates produced from original concretes of distinctly different quality, and recycled aggregates produced by means of different production methods shall be stored separately.
2. Recycled coarse aggregate and recycled fine aggregate shall be stored separately.
3. Recycled aggregate shall be stored and transported in a manner to prevent breakage and segregation or otherwise cause change in quality of the recycled aggregate concerned.
4. Water absorption ratio of recycled coarse aggregates is large; therefore, such aggregates should normally be used in a saturated and surface dry condition. For this reason recycled aggregate storage yards should be provided with water sprinkling facilities so that recycled coarse aggregates can be maintained at the required moist condition. However, some un-hydrated Portland cement and hydrated lime is present in fine recycled aggregates, and there is danger that such fine aggregates in time shall become caked. Therefore, fine recycled aggregates should not be kept in storage for any longer period of time. It is left to the ready mixed concrete manufacturers to solve this problem.
5. Recycled aggregates shall be stored separate from other types of aggregates.
6. It is recommended that if different types and qualities of recycled aggregate are produced, the plant should not process colored material such as brick rubble together with concrete rubble because of the extra cost which is involved in the cleaning of processing units when changing from brick to concrete rubble.

4.2 Quality of Recycled Aggregates

Simply producing a clean, crushed and well-graded material is not sufficient to ensure effective recycling. The recycled material produced must be suitable for specific applications and it should comply with certain grading limits, contain minimal levels of contamination and meet other requirements of stability and durability. Once the concrete has been crushed, sieved and if necessary decontaminated, it can find applications as 1) general bulk fill, 2) fill in drainage projects, 3) sub-base or base material in road construction or 4) aggregate for new concrete. The following paragraphs shall primarily discuss recycled aggregate for production of new concrete and for other purposes as well.

4.2.1 Grading, Particle Shape and Surface Texture of Recycled Aggregates

After a screening on an ASTM No. 4 (5 mm) sieve, the grading of an average crusher products is compared with ASTM C-33 grading requirements for a 25 mm (1 in) maximum size aggregate shown in figure 4.6. Both of the coarse aggregates were produced by the crushing of original concrete in a jaw crusher (Hansen, 1992).

It is evident that both aggregates could have been brought within ASTM grading requirements by slight adjustments of the opening of the crusher. Apparently it is easy to produce reasonably well-graded coarse recycled aggregate by means of a jaw crusher.

The grading of fine crusher products below 5 mm from three different investigations (Hansen, 1992) are compared in figure 4.7. All gradings fall within the shaded of the sieve diagram in figure 4.7. All were produced by the crushing of old concretes in a jaw crusher. It will be seen that all gradings are somewhat coarser than the lower limit of ASTM grading requirements. Some are even lower than the permissible grading limit of zone 1 sand in British Standard 882, 1201, which is considered to be the coarsest grading of sand from which concrete of reasonable quality can be produced.

It may be concluded that fine recycled aggregates, as they come from the crusher, are somewhat coarser and more angular than desirable for production of good concrete mixes.

As fine recycled aggregates also consist of angular particles, it is not surprising that concretes which are produced exclusively with coarse and fine recycled aggregates tend to be harsh and unworkable (Hansen, 1992). However, by adding a certain amount of finer natural blending sand it is possible to bring fine recycled aggregates within the grading limits of ASTM C-33. At the same time, concrete workability is generally improved (Hansen, 1992).

It was found that the quantity of material finer than 75 micron in 38 mm (1 1/2 in) maximum size coarse recycled aggregates ranged from 0.3% to 0.5% (Hansen, 1992). In fine recycled aggregate below the ASTM No. 4 sieve, material finer than 75 micron ranged from 4.1% to 6.6% depending on concrete quality. In one particular case where original concrete consisted essentially of cement mortar, the corresponding value was 9.1%. Moreover, it was found out that 25 mm maximum size coarse recycled aggregate to contain between 1.3% and 1.7% particles finer than 88 micron, depending on the quality of concrete (Hansen, 1992).

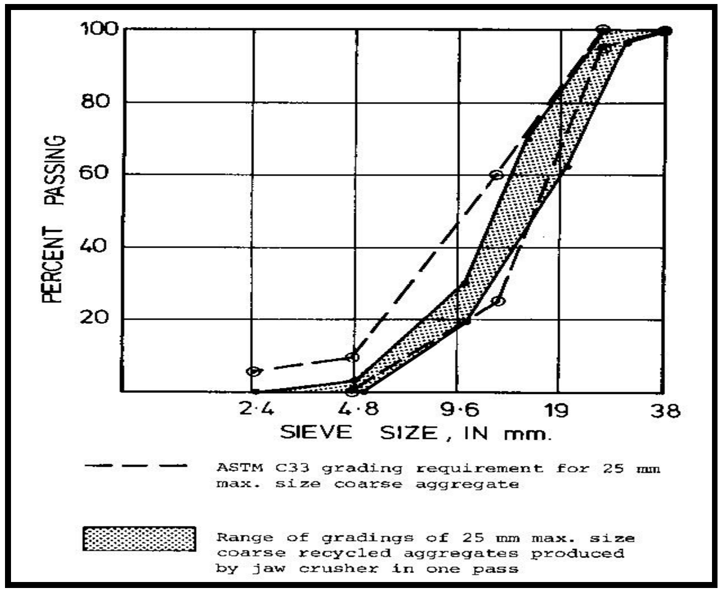


FIGURE 4.6: RANGE OF GRADINGS OF 25 MM COARSE RECYCLED AGGREGATE PRODUCED BY JAW CRUSHER IN ONE PASS, (HANSEN, 1192)

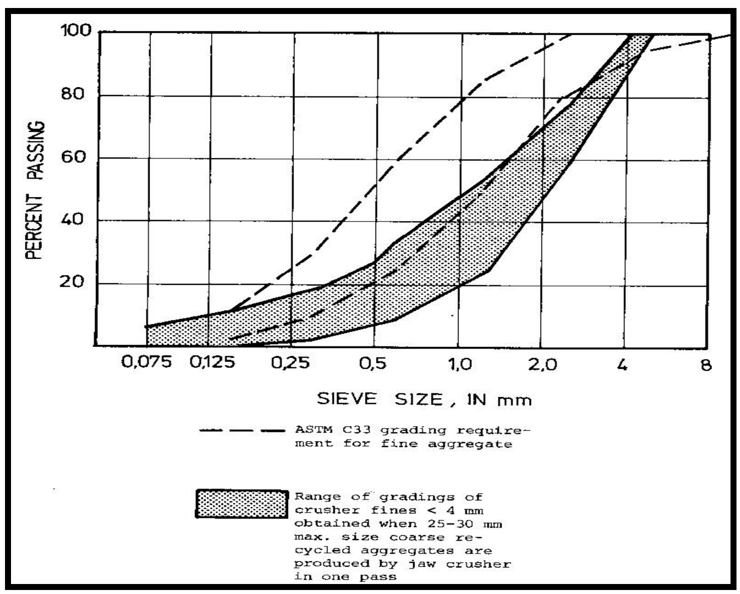


FIGURE 4.7: RANGE OF GRADINGS OF CRUSHER FINES < 4MM (FINE AGGREGATE) OBTAINED WHEN 25-30 MM MAX SIZE COARSE PRODUCED, (HANSEN, 1992)

Hansen and Narud found that material finer than 75 micron in fine recycled aggregates below 4 mm ranged from 0.8% to 3.5%, depending on concrete quality (Hansen & Narud, 1983).

Considering that ASTM C-33 allows 1.5% dust of fracture in coarse aggregates, 5% dust in fine aggregate in concrete which is subject to abrasion, and 7%

in all other concrete, it may be concluded that recycled aggregates in most cases can be used for production of concrete without being washed.

Schulz concluded that recycled concrete aggregates will be adequate for production of new concrete only if particle sizes below 2 mm are screened out (Schulz, 1986).

In conclusion, for the grading and shape of aggregates, fine recycled aggregates are not preferred as they are usually coarser and more angular than that desired for concrete. However, this can be improved by adding finer natural blending sand in order to bring fine recycled aggregates within the grading limits of ASTM C-33. On the other hand, the coarse recycled aggregates are usually coping with ASTM C-33 and this could be seen in figure 4.6.

4.2.2 Attached Mortar and Cement Paste

When old concrete is crusher, a certain amount of mortar remains attached to the stone particles in the recycled aggregates. Table 4.4 shows the volume percentage of old mortar which remained attached to original gravel particles in recycled aggregate, as reported by Hansen and Narud on the basis of an investigation by Hedegaard in 1981.

A representative sample of various grades and size fractions of recycled aggregate was mixed with red-colored cement and cast into cubes. After handling, the cubes were cut into slices and the slices polished. Mortar attached to natural gravel particles in recycled aggregates could be clearly distinguished both from the original gravel particles and from the red cement matrix.

The volume percentage of old mortar, which was attached to gravel particles in each grade and size fraction of recycled aggregate, was determined on a representative number of samples by means of a linear traverse method, similar in principle to the method which is described in ASTM C-457-71, 'Standard recommended practice for microscopical determination of air-void content and parameters of the air-void system in hardened concrete' (Hansen, 1992).

Hansen and Narud in 1983 found the volume percentage of mortar attached to natural gravel particles to be between 25% and 35% for 16-32 mm coarse recycled aggregates, around 40% for 8-16 mm coarse recycled aggregates, and around 60% for 4-8 mm coarse recycled aggregates (see table 4.4). However, it appears that for the same cement and original aggregate the volume percentage of old mortar attached to recycled concrete aggregates does not vary much even for widely different water-cement ratios of original concrete.

Hansen (1992) mentioned that 35.5% of old mortar attached to natural gravel particles in 25-5 mm coarse recycled aggregate produced by the crushing of original concrete having a compressive strength of 24 MPa. Corresponding figures were 36.7% mortar for 41 MPa concrete and 38.4% for 51 MPa concrete.

Figure 4.8 shows the results of a Japanese investigation reported by B.C.S.J (B.C.S.J., 1978) where the hydrated cement paste adhering to recycled aggregates was determined by immersing the particles in a dilute solution of hydrochloric acid at 20º C. It will be seen that the amount of cement paste attached to sand or stone particles, as determined from the weight loss due to dissolution of cement during the test, increases with decreasing the particle size of aggregate. Approximately 20% of cement paste is attached to 20-30 mm of aggregate; while the 0-0.3 mm filler fraction of recycled fine aggregate contains 45-65% of old cement paste. Old cement paste and mortar in many cases unfavorably affect the quality of recycled concretes, and it should be avoided to use the finer fractions below 2 mm.

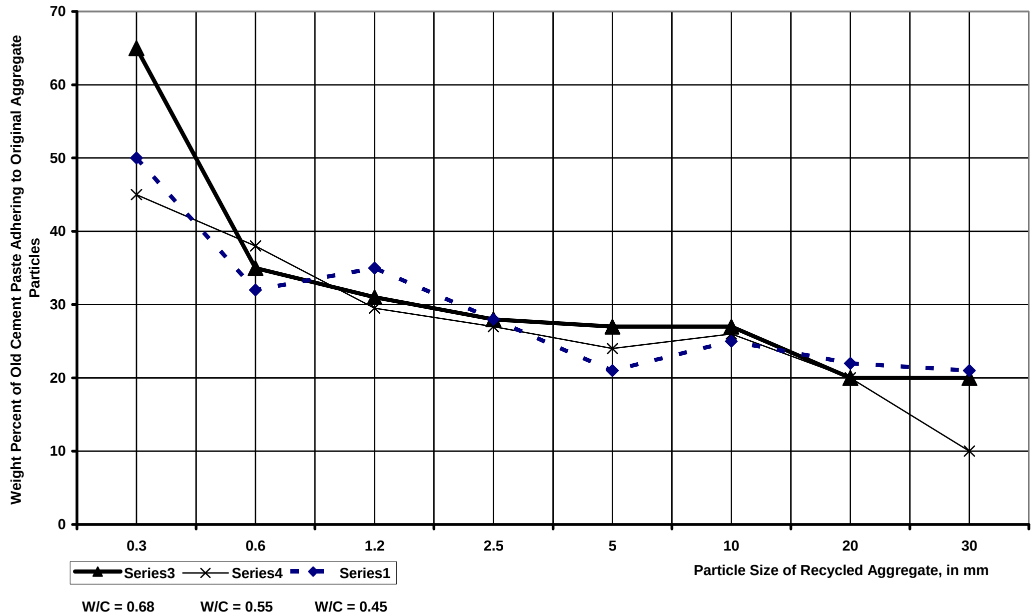


FIGURE 4.8: WEIGHT % OF CEMENT PASTE WITH DIFFERENT W/C RATIOS, (HANSEN, 1992)

In conclusion, the attached mortar and cement past represent a weak point in the recycled aggregate as they might affect the quality of concrete. The amount of cement paste attached to the particles of the recycled aggregates decrease with increasing the particle size, i.e. increase with decreasing the particle size.

4.2.3 Density

Hansen and Narud (1983) found densities of coarse recycled aggregates in saturated and surface dry condition ranging from 2340 kg/m^3 (for 4-8 mm material) to 2490 kg/m^3 (for 16-32 mm material), independent of the quality of original concrete, see table 4.4. Corresponding SSD densities of original coarse aggregates ranged from 2500 kg/m^3 to 2610 kg/m^3. As stated by Hansen (1992), Narud found an SSD density of 2279 kg/m^3 for fine aggregates produced from a particular original concrete which was made with a water-cement ration of 0.70.

Table 4.4: Properties of Natural Gravel and Recycled Aggregates, (Hansen & Narud, 1983)

Type of Aggregate	Size Fraction in mm	Specific Gravity SSD cond.	Water Absorption in %	LA Abrasion % (L500)	Los Angeles Uniformity Number L100/L500 Ratio	B.S. Aggregate Crushing Value in Percent	Volume Percent of Mortar Attached to Natural Gravel Particles
Original Natural Gravel	4-8	2500	3.7	25.9	0.28	21.8	0
	8-16	2620	1.8	22.7	0.22	18.5	0
	16-32	2610	0.8	18.8	0.20	14.5	0
Recycled Aggregate (H) (w/c = 0.40)	4-8	2340	8.5	30.1	0.30	25.6	58
	8-16	2450	5.0	26.7	0.25	23.6	38
	16-32	2490	3.8	22.4	0.24	20.4	35
Recycled Aggregate (M) (w/c = 0.70)	4-8	2350	8.7	32.6	0.31	27.3	64
	8-16	2440	5.4	29.2	0.28	25.6	39
	16-32	2480	4.0	25.4	0.25	23.2	28
Recycled Aggregate (L) (w/c = 1.20)	4-8	2340	8.7	41.4	0.38	28.2	61
	8-16	2420	5.7	37.0	0.39	29.6	39
	16-32	2490	3.7	31.5	0.38	27.4	25
Recycled Aggregate (M) (w/c = 0.70)	< 5	2280	9.8	---	---	---	---

Table 4.5: SSD-Densities and Water Absorption of Original Mortars Referring to Recycled Aggregates in Table 4.4, (Hansen & Narud, 1983)

Water/Cement	Size of Fraction in mm	Density in kg/m^3	Water Absorption in Percent
0.40	4-8	2036	17.0
	8-16	2060	17.0
	16-32	2148	15.6
0.70	4-8	2041	17.0
	8-16	2060	16.2
	16-32	2091	15.8
1.20	4-8	2070	16.5
	8-16	2068	16.6
	16-32	2081	16.5

Table 4.5 shows densities of old mortars in original concretes which were used to produce coarse recycled aggregates, the properties of which are shown in table 4.4. It will be shown that densities around 2000 kg/m^3 are obtained for such mortars. This is much lower than the densities of corresponding hardened concretes which ranged from 2380 to 2401 $kg/m^{3.}$

Hansen (1992) mentioned that Hasaba found that the SSD density of 25-5 mm coarse recycled aggregate to be around 2430 $kg/m^{3,}$ independent of the quality of original concrete, see table 4.6. The density of corresponding fine recycled aggregates below 5 mm was 2310 kg/m^3. The density of corresponding original coarse aggregate was 2700 kg/m^3 and 2590 kg/m^3 for original fine aggregate.

In another Japanese investigation reported by B.C. S.J in 1978 dry densities of coarse recycled aggregates varied between 2120 kg/m^3 and 2430 kg/m^3, corresponding to SSD densities between 2290 kg/m^3 and 2510 kg/m^3 for recycled aggregates from a wide range of original concretes. Dry densities of corresponding fine recycled aggregates ranged from 1970 kg/m^3 to 2140 kg/m^3, and SSD densities ranged from 2190 kg/m^3 to 2320 kg/m^3.

SSD densities of recycled aggregate must be determined in the laboratory before any mix design of recycled aggregate concrete can be attempted. For what concerns coarse recycled aggregates this can be done according to ASTM designation C-127, 'Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate'. For what concerns fine recycled aggregate such determination by means of the corresponding ASTM designation C-128 is very difficult because it is difficult to determine when fine recycled aggregate is in SSD condition. It must also be kept in mind that any subsequent variation in density of recycled aggregate during concrete production will give rise to variations, not only in mix proportions and therefore concrete properties, but also in yield of concrete produced (Hansen, 1992).

It may be concluded that the density of recycled aggregate is somewhat lower than the density of original aggregate due to a relatively low density of the old mortar which is attached to the original aggregate particles. However, for the same cement and original aggregate the density of recycled concrete aggregate does not vary much even for widely different water-cement ratios of original concrete.

Table 4.6: Properties of Natural Gravel and Recycled Aggregates,, (Hansen, 1992)

Type of Aggregate	Density (SSD) in kg/m^3	Water Absorption %	B.S. Aggregate Crushing Value in %	B.S. 10% Fineness Value, kN	Sodium Sulphate Soundness % Loss	Content of Old Mortar Volume %
15 mm max size natural gravel	2700	1.14	---	---	---	---
25 mm max size recycled, w/c = 0.42	2430	6.76	23.0	133	23.9	38.4
26 mm max size recycled, w/c = 0.53	2430	6.93	23.1	130	23.1	36.7
27 mm max size recycled, w/c = 0.74	2430	7.02	24.6	113	28.6	35.5
Unspec. Fine recycled aggregate < 5 mm	2310	10.9	---	---	---	---

Hansen (1992) stated that it was also found that the density in loosely packed conditions of a certain type of recycled concrete aggregates was 1350 kg/m^3 compared to 1440 kg/m^3 for natural gravel in the same condition. Schulze has shown general relationships between on one hand particle density and water absorption of recycled demolition debris, and on the other hand density of such materials in loosely packed condition. Such relationships could be useful for primitive mix design of concrete by volume (Schulz, Ibid. Ref. 135).

4.2.4 Water Absorption

In an earlier review paper, Nixon (1978) concluded that the most marked difference in physical properties of recycled concrete aggregates compared with conventional aggregates is higher water absorption.

Hansen and Narud (1983) found water absorptions of coarse recycled aggregates ranging from 8.7% for 4-8 mm material to 3.7% for 16-32 mm material, regardless of the quality of original concrete, see table 4.4. Corresponding water absorptions of original aggregates ranged from 3.7% to 0.8%. Table 4.5 shows the water absorptions of old mortar in original concretes, which were used to produce recycled concrete aggregates, the properties of which are shown in table 4.4. It will be seen that water absorptions around 17% are obtained for such mortars, which is much higher than overall water absorptions for recycled aggregates. Hansen (1992) mentioned that Narud has found water absorption of 9.8% for fine recycled aggregate produced from an original concrete with a water-cement ratio of 0.70 corresponding to designation M in table 4.4.

Also Hansen (1992) mentioned that Hasaba found water absorptions around 7% for 25-5 mm coarse recycled aggregates, independent of the quality of original concretes. Corresponding water absorptions for fine recycled aggregates below 5 mm were around 11%, see table 4.6. Both values are in good agreement with results obtained by Hansen and Narud which are presented in table 4.4. In another investigations reported by B.C.S.J (1978), water absorptions of recycled coarse aggregates between 3.6% and 8.0% were found for coarse recycled aggregates, and absorptions between 8.3% and 12.1% were found for fine recycled aggregates. Similar results were found by Ravindrarajah and Tam (1985).

According to the Japanese Proposed Standard for the 'Use of recycled aggregate and recycled aggregate concrete' (B.C.S.J., 1977), recycled aggregates should not be used for concrete production when water absorption is more than 7% for coarse aggregate and more than 13% for fine aggregate. It would appear from what was mentioned before that most recycled aggregates would be meeting such requirements.

Water absorption of coarse and fine recycled aggregates must be determined in the laboratory before any mix design of recycled aggregate concrete can be attempted. For what concerns coarse recycled aggregate this may be done according to ASTM C-127, 'Standard test method for specific gravity and absorption of coarse aggregate'. According to Hansen (1992), Kreijger has found parabolic relation between water absorption and density of recycled aggregates as shown in figure 4.9.

It is more difficult to determine water absorption capacity and water content of fine recycled aggregate than of coarse recycled aggregate. Hansen found the use of ASTM C-128 'Standard test method for specific gravity and absorption of fine aggregate' to be inappropriate and highly inaccurate when used to assess when fine recycled aggregates are in a saturated and surface dry-condition. The material is too sticky. As a consequence, it is difficult to control the effective water-cement ratio of a concrete production whether in the laboratory, in a ready mixed concrete plant or on site, if concrete is produced with fine recycled aggregate. Considering that fine recycled aggregates also increase the water demand of fresh concrete and lower the strength and probably the durability of hardened concrete, it is not recommended to use recycled fine aggregate for production of quality concrete (Hansen, 1992).

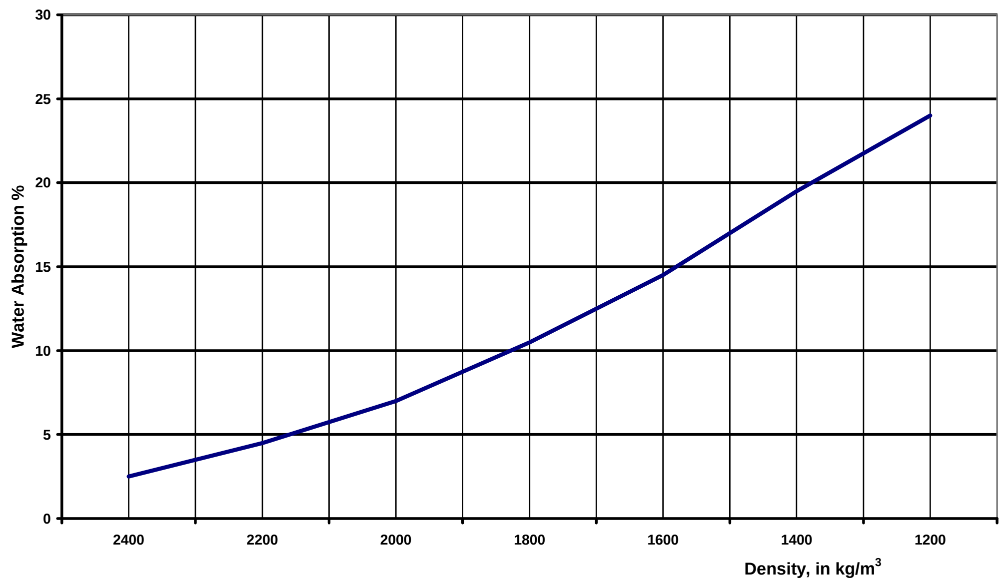


FIGURE 4.9: WATER ABSORPTION AS A FUNCTION OF DENSITY OF RCA, (HANSEN, 1992)

It may be concluded that the water absorption of coarse recycled aggregates is much higher than the water absorption of original aggregates. This is due to the higher water absorption of old mortar attached to original aggregate particles. Water absorption of not more than 7% for coarse recycled aggregate and 13% for fine recycled aggregate should not be allowed.

4.2.5 Los Angeles Abrasion and British Standard Crushing Value

From table 4.4, it can be seen that the Los Angeles (LA) abrasion loss percentage is ranging from 22.4% for 16-32 mm coarse recycled aggregate produced from a high strength original concrete, to 41.4% for 4-8 mm coarse recycled aggregate produced from a low strength original concrete. Corresponding LA uniformity numbers L100/L500 were 0.24 and 0.38. BS aggregate crushing values were 20.4% and 28.2% respectively (Hansen, 1992).

In table 4.6, BS aggregate crushing values range from 23.0% for 25-5 mm coarse recycled aggregate produced from an original high strength concrete to 24.6% for a 25-5 mm coarse recycled aggregate produced from an original low strength concrete. Corresponding BS 10% fineness values were 13.3 tons and 11.3 tons. B.C.S.J found Los Angeles abrasion loss percentage ranging from 25.1% to 35.1% for coarse recycled aggregates from 15 different concretes of widely different strengths, which were crushed in different ways.

Table 4.7 shows that Los Angeles loss percentages range from 20.1% for a 13-5 mm coarse recycled aggregate produced from an original high strength (40 MPa) concrete to 28.7% for a 13-5 mm recycled aggregate produced from an original low strength (16 MPa) concrete (Hansen, 1992).

Table 4.7: Relationship between compressive strengths of original concretes and LA loss % of corresponding recycled aggregates, (Hansen, 1992)

Sample	**C**	**A**	**B**	**E**	**F**	**D**
Compressive Strength (Mpa)	15	16	21	30	38	40
LA Abrasion Loss (%)	28.7	27.3	28.0	25.6	22.9	20.1

According to ASTM C-33, 'Standard specification for concrete aggregates', aggregate may be used for production of concrete when the Los Angeles abrasion loss percentage does not exceed 50%. Crushed stone for road construction purposes is usually required to have LA loss value not exceeding 40%.

According to British Standard 882, 1201, Part 2, 1973, 'Specifications for aggregates from natural sources', aggregates may be used for production of concrete wearing surfaces when the aggregate crushing value does not exceed 30%, or 45% for other concrete, as determined according to BS 812, 'Methods for sampling and testing of mineral aggregates'. Alternatively, BS 882 specifies that the BS 10% fines values should be more than 5 tons for normal concrete, more than 10 tons for concrete wearing surfaces, and more than 15 tons for granolithic floor finishes.

Considering the results reported above, it may be concluded that recycled concrete aggregates from all but the poorest quality concrete can be expected to pass ASTM and BS requirements to LA abrasion loss percentage, BS crushing value, as well as BS 10% fines value even for production of concrete wearing surfaces, but probably not for granolithic floor finishes. Los Angeles abrasion loss percentage should not exceed 50% for the production of normal concrete. The 10% fines value should be more than 5 tons (50 kN) for normal concrete, 10 tons (100 kN) for concrete wearing surfaces and 15 tons (150 kN) for granolithic floors. The BS crushing value should not be more than 45% for recycled aggregate.

4.2.6 Sulfate Soundness

ASTM C-33, 'Standard specification for concrete aggregate', limits the loss in weight when aggregate is subjected to five cycles of alternate soaking and drying in a Sulfate solution. The test is carried out according to ASTM C-88, 'Standard test method for soundness of aggregates by use of sodium Sulfate or magnesium Sulfate'. When magnesium Sulfate is used, ASMT C-33 limits the weight loss of coarse and fine aggregate to 18% and 15%, respectively. Corresponding weight losses are 12% and 10% when sodium sulfate is used.

It was found out that there is a sulfate soundness loss of 3% for coarse recycled concrete aggregate compared with 5% for corresponding virgin aggregates (Hansen, 1992).

B.C.S.J (1977) found sodium sulfate soundness loss percentages after five cycles ranging from 18.4% to 58.9% for coarse recycled aggregates from 15 original concretes of different compressive strengths and crushed in different ways. Sulfate soundness loss percentage for corresponding fine recycled aggregates ranged from 7.4% to 20.8%. Kaga *et al*. claimed that the most recycled aggregates would be less durable than original aggregates, and that recycled aggregates would fail to meet ASTM C-33 requirements to sodium sulfate soundness of not more than 12% loss for coarse aggregate (Kaga, Kasai, Takeda, & Kemi, 1986).

Contrary to this, Hansen (1992) mentioned that it was found that magnesium sulfate soundness losses range from 0.9% to 2.0% for coarse recycled aggregates produced from concrete, which was derived from a number of different pavements. Corresponding loss values of fine recycled aggregates ranged from 6.8% to 8.8%. Losses of 3.9% and 7.1% were measured for original coarse and fine aggregate used to produce original concretes.

On the basis of the above mentioned, Hansen stated that it could be seen that coarse recycled aggregates were superior to control natural gravel in those tests designed to evaluate the possible effect of aggregate properties with respect to the durability of concrete. He also mentioned that durability of fine recycled aggregates was comparable to durability of control natural sand.

In conclusion, further testing and investigations are recommended for sulfate soundness since different results from various laboratory tests have been developed. However, the RILEM specifications for recycled aggregate require that the maximum content of sulfates should not be more than 1%.

4.2.7 Contaminants

One of the problems inherent in the use of recycled aggregates for the manufacturing of new concrete is the possibility of contaminants in original demolition debris passing into new concrete. Contaminants may be in the form of clay balls, bitumen joint seals, expansion joint fillers, gypsum, refractory bricks, chlorides, organic materials, chemical admixtures, steel and other metals, glass, lightweight bricks and concrete, fire damaged particles, particles susceptible to frost or alkali reactions, industrial chemical sands, reactive substances and high alumina cement concrete.

B.C.S.J (1977) reported results of a study of the effect on concrete strength of various contaminants which were added independently and in various quantities to a natural and a recycled aggregate.

Table 4.8 shows the volume percentage of each of six contaminants which, when added to the aggregate, gave 15% reduction of compressive strength compared to control concretes.

Table 4.8: Volume % of impurities giving 15% reduction in strength, (B.C.S.J., 1978)

Impurities	Lime Plaster	Soil	Wood	Hydrated Gypsum	Asphalt	Paint made of Vinyl Acetate
Volume % of Aggregate	7	5	4	3	2	0.2

From the results of the B.C.S.J study (1977), it may be concluded that impurities in the form of tiles and window glass have little influence on the compressive strength of recycled aggregate concrete. However, blast furnace slag aggregate may give slightly lower concrete strength. Concrete with 3% by weight of gypsum plaster reduces strength by 15% when concrete is dry-cured and by up to 50% when concrete is wet cured. This is because gypsum plaster is softened and weakened by water immersion. Clay, acetic vinyl paint, asphalt, and wood also reduced concrete strength.

On the basis of such results, the Japanese Proposed Standard for the 'Use of recycled aggregate and recycled aggregate concrete' (B.C.S.J., 1977) limits the amounts of injurious impurities contained in recycled aggregates to the values shown in table 4.9.

Table 4.9: Weight of impurities giving reduction in strength, (B.C.S.J., 1977)

Type of Aggregate	Plasters, Clay lumps & Other Impurities of Densities < 1950 kg/m^3	Asphalt, Plastics, Paints, Cloth, Paper, Wood & Similar Material Particles Retained on a 1.2 mm Sieve. Also Other Impurities of Densities < 1200 kg/m^3
Recycled Coarse	10 kg/m^3	2 kg/m^3
Recycled Fine	10 kg/m^3	2 kg/m^3

Hansen (1992) stated that the properties of hardened concrete made from unwashed and washed coarse recycled aggregate were studied. Three different methods of washing were employed. It was found out that the compressive strength of recycled aggregate concrete is increased by the washing of coarse aggregate, but the carbonation depth increases at the same time, probably due to removal of fines. Thus, the concrete becomes stronger but more permeable. There appears to be no difference in drying shrinkage of concretes made with washed and unwashed recycled concrete aggregates.

It may be concluded that provided the usual limits of cleanliness are applied to recycled aggregates and a strict limit is imposed on the total amount of allowable impurities, than of those contaminants, only glass is likely to remain a potential problem. Waste glass is a problem because it is alkali reactive with cement paste under wet conditions. This is made more serious by the lack of suitable means of removing glass contaminants. Therefore, it is preferable to ensure that no glass is present in the original debris. Plate glass windows should always be removed from buildings before demolition. Also gypsum plaster should be avoided as it may reduce the compressive strength of concrete. Thus, contaminants should not be allowed for more than 2 kg/m^3 for asphalt, plastics, paints, cloth, paper, wood and similar material particles retained on a 1.2 mm sieve and also other impurities of densities less than 1200 kg/m^3, and not more than 10 kg/m^3 for plasters, clay lumps and other impurities of densities less than 1950 kg/m^3.

4.3 Mechanical Properties of Recycled Aggregate Concrete

4.3.1 Compressive Strength and Rate of Strength Development

Before attempting to review the mechanical properties and durability of recycled aggregate concrete it may be appropriate to mention that Japanese researchers (Hansen, 1992) agree up to 30 percent of natural aggregate can be replaced by recycled concrete aggregate without significantly changing the properties of new concretes as compared to corresponding control concretes made with natural aggregates.

Recycled Aggregate Concrete Made with Coarse Recycled Aggregate and Natural Sand

On the basis of his review of earlier research, Nixon (1978) concluded that the compressive strength of recycled aggregate concrete is somewhat lower, in some cases up to 20% lower but usually less, compared with the strength of control mixes of conventional concrete. B.C.S.J (1977) arrived at the same conclusion on the basis of experimental results which showed compressive strength of recycled aggregate concrete to be between 14% and 32% lower than that of conventional concrete.

Hansen reported that Wesche and Schulz compiled earlier results obtained by Buck, Malhotra, Schulz and Frondistou-Yannas. Apparent correlation was found between compressive strengths of conventional and recycled aggregates concretes (Hansen, 1992). Figure 4.10 shows the compressive strengths of recycled aggregate concretes as a function of the strength of original concretes as found by Buck, Malhotra, Schulz and Frondistou-Yannas.

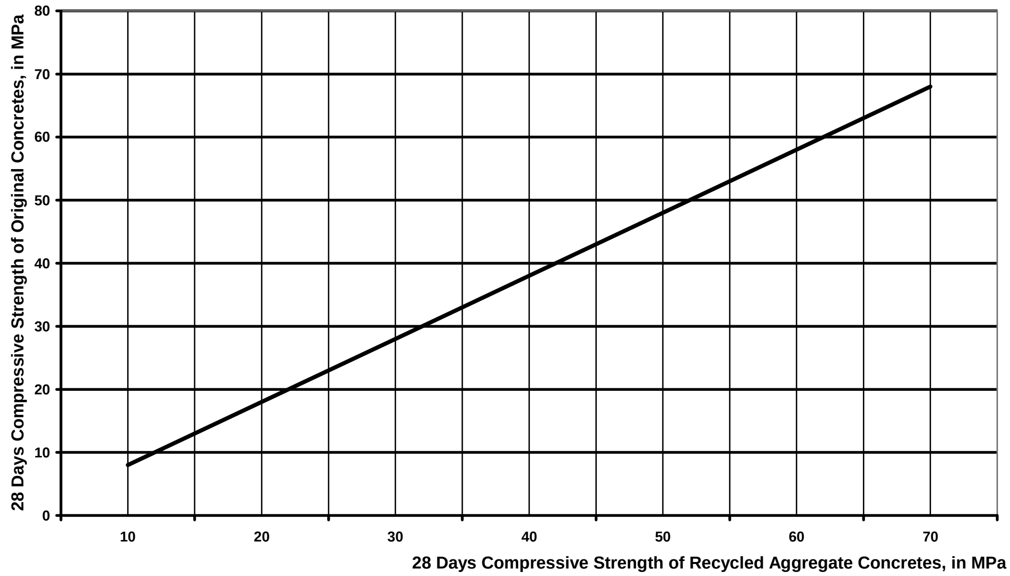


FIGURE 4.10: COMPRESSIVE STRENGTHS OF RECYCLED AGGREGATE CONCRETES AS A FUNCTION OF THE STRENGTH OF ORIGINAL CONCRETES, (HANSEN, 1992)

As seen in table 4.10, the results present that in three independent series of experiments performed by Hansen and Narud (1983), recycled aggregate concretes made with coarse recycled aggregate and natural sand obtained approximately the same strength and in some cases higher strength than corresponding control concretes which were made with the same mix proportions, but entirely with natural aggregates (H/H versus H, M/M versus M, L/L versus L in table 4.10). It is shown in the table that when high-strength concrete (H) was produced from low-strength recycled aggregate (L) and natural sand, the compressive strength of the recycled concrete mix (H/L) was 39% lower than the compressive strength of recycled concrete mix (H/H) which was produced with high-strength coarse recycled aggregate and natural sand.

Table 4.10A: Compressive Strength in MPa of Original and Recycled Aggregate Concrete made with Natural Sand and Coarse Recycled Aggregate after 38 days of Accelerated Curing, (Hansen & Narud, 1983)

Series	Compressive Strength of Original & Recycled Aggregate Concrete[a], in MPa											
	H	H/H	H/M	H/L	M	M/H	M/M	M/L	L	L/H	L/M	L/L
1	56.4	61.2	49.3	34.6	34.4	35.1	33.0	26.9	13.8	14.8	14.5	13.4
2	61.2	60.7	---	---	36.0	---	36.2	---	14.5	---	---	13.6
3	58.5	60.6	---	---	33.2	---	36.0	---	15.0	---	---	12.8

Table 4.10B: Compressive Strength in MPa of Original and Recycled Concretes made with both Coarse and Fine Recycled Aggregate, (Hansen & Narud, 1983)

		Compressive Strength of Original & Recycled Aggregate Concrete, in MPa											
Series	Curing Time	H	H/H	H/M	H/L	M	M/H	M/M	M/L	L	L/H	L/M	L/L
4	14 days in water at 20 C	49.5	37.3	33.6	33.7	23.9	16.1	17.2	19.1	9.7	5.5	4.5	6.8
5	204 days in water at 20 C	56.1	51.4	45.7	38.9	38.9	24.9	25.8	24.3	17.0	9.3	6.8	10.3

Hansen and Narud (1983) concluded that the compressive strength of recycled aggregate concrete depends on the strength of the original concrete, and that it is largely controlled by a combination of the water-cement ratio of the original concrete and the water-cement ratio of the recycled concrete when other factors are essentially identical. If the water-cement ratio of the original concrete is the same as or lower than that of the recycled aggregate concrete, then the strength of the recycled aggregate concrete can be as good as or higher than the strength of the original concrete.

B.C.S.J (1978) obtained somewhat similar results using coarse recycled aggregate and natural sand as seen in table 4.11.

[a] Symbols H, M and L indicate original high-strength, medium strength & low strength concretes made with natural gravel. Symbol H/M indicates a high-strength, recycled concrete made with coarse recycled aggregate produced from medium-strength concrete, etc.

Table 4.11: Compressive Strength in MPa of Original and Recycled Aggregate Concretes made from the same original concretes using Recycled Coarse Aggregate and Various Proportions of Recycled Fine Aggregate and Natural Sand, (B.C.S.J., 1978)

w/c	Compressive Strength of Concrete, MPa			
	Natural Coarse & Fine Aggregate (Original Concrete)	Recycled Coarse Aggregate & 100% Natural Sand	Recycled Coarse Aggregate, 50% Recycled Fine Aggregate & 50% Natural Sand	Recycled Coarse Aggregate & 100% Recycled Fine Aggregate
0.45	37.5	37.0	34.0	30.0
0.55	28.9	28.5	25.0	21.5
0.68	22.0	21.0	17.5	13.0

Recycled Aggregate Concrete Made with Coarse and Fine Recycled aggregates

Hansen (1992) reported that based on equal water-cement ratios the use of both coarse and fine recycled aggregates on average reduced the compressive strength of recycled concretes by approximately 30% compared to control concretes made with natural sand and gravel. Thus, the use of fine recycled aggregate always has a detrimental effect on the compressive strength of recycled concretes.

From table 4.11 (B.C.S.J., 1978), it is seen that the compressive strength of recycled aggregate concretes made with coarse recycled aggregates and a blend of 50% fine recycled aggregate and 50% natural sand was 10-20% lower than the strength of a corresponding recycled concrete made with coarse recycled aggregate and 100% natural sand. When recycled aggregate concretes were made with coarse recycled aggregate and 100% fine recycled aggregate, the compressive strength was 20-40% lower than the strength of corresponding recycled aggregate concrete made with coarse recycled aggregate and 100% natural sand.

Also from figure 4.11, it can be seen that one particular recycled aggregate concrete lost half its compressive strength when all natural sand in the mix was replaced by fine recycled aggregate. It is also observed that loss of strength is much more severe when natural sand is replaced by fine recycled aggregate in the entire grading spectrum of the sand (lower curve in figure 4.11) than when replacement takes place in the coarser fractions only (upper curve in figure 4.11). In other words, it appears to be the fractions finer than 2 mm of recycled aggregate which bring about the largest strength reductions of recycled aggregate concrete.

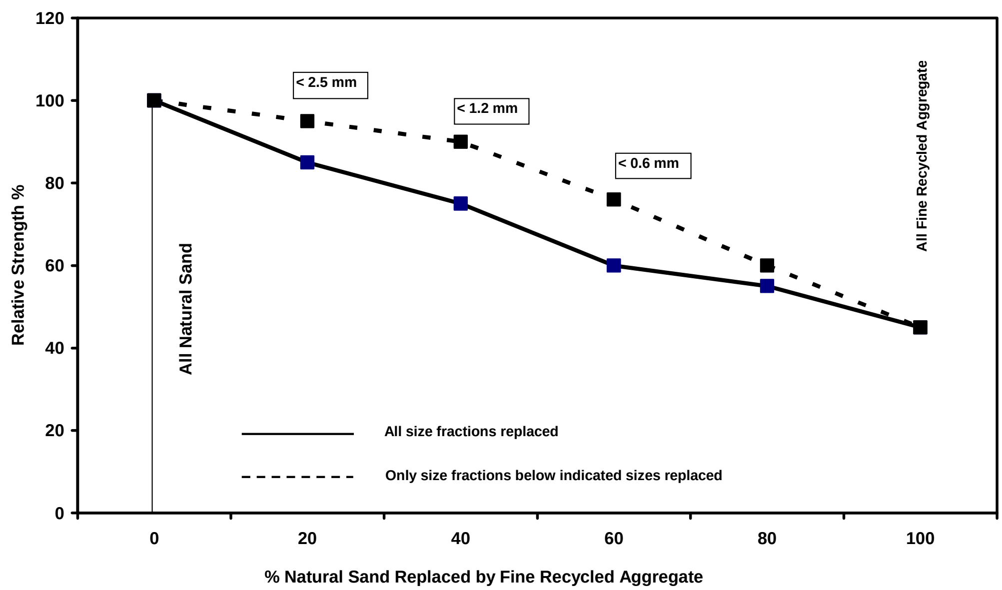


FIGURE 4.11: COMPRESSIVE STRENGTHS OF RECYCLED AGGREGATE CONCRETES MADE WITH A W/C RATIO OF 0.65 WHERE VARIOUS VOLUME PERCENTAGES OF NATURAL SAND WERE REPLACED BY FINE RECYCLED AGGREGATE, (HANSEN, 1992)

In conclusion, the compressive strength requirements for recycled aggregate concrete depend on the strength of the original concrete being recycled and also controlled by the w/c ratio of the recycled concrete. Compressive strengths of recycled coarse aggregate concrete could show acceptable results as they are lower than that of conventional concrete by not more than 1.3% to 4.5% in the case of using recycled coarse aggregate with 100% natural sand.

Effect of Dry Mixing of Aggregate

It was found by Kasai (Kasai, Hisaka, & Yanaga, 1986) that the fineness modulus of recycled aggregates to be reduced with increasing the time of dry mixing in the concrete mixer before cement and water are added (figure 4.12).

It was also found by him that the compressive strength, tensile strength and modulus of elasticity of recycled aggregate concretes, made with recycled aggregates which had been dry-mixed prior to production of concrete, to be considerably higher than those attained for concretes made with recycled aggregates which had not been dry-mixed prior to addition of water and cement (see table 4.12).

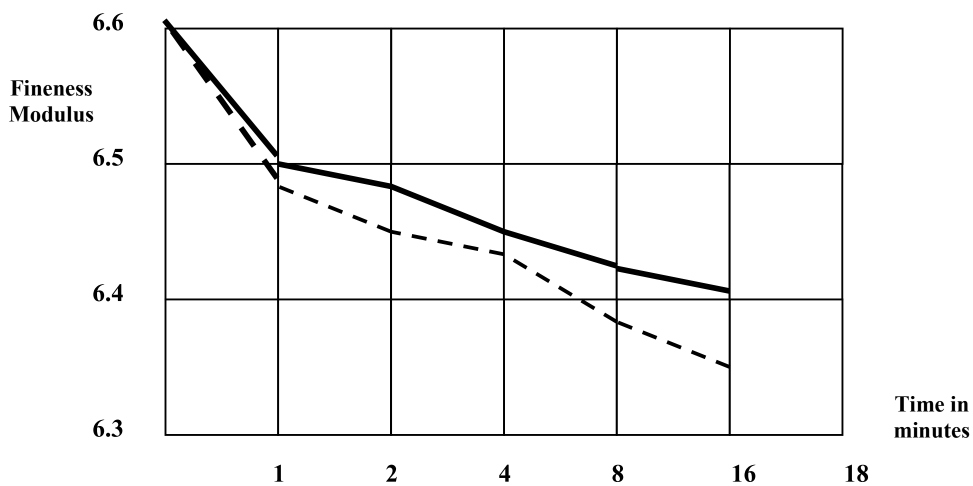


FIGURE 4.12: REDUCTION OF FINENESS MODULUS OF COARSE RECYCLED AGGREGATE AS A FUNCTION OF DRY MIXING TIME, (HANSEN, 1992)

***Notes on figure 4.12*:**

- Solid line is for w/c = 0.5 of original concrete, and dashed line is for w/c = 0.6.
- X-axis represents the 'Dry-mixing time in minutes'.
- Y-axis represents the 'Fineness Modulus'.

Table 4.12: Effects of Dry Mixing of Recycled Aggregates Prior to Addition of Cement and Water on Strength and Modulus of Elasticity of Recycled Aggregate Concretes, (Kasai, Hisaka & Yanaga, 1986)

Dry Mixing	w/c	Slump (cm)	Compressive Strength in % of Controls			Tensile Strength in % 28 days	Modulus of Elasticity in % 28 days
			3 days	7 days	28 days		
No	0.5	6.5	100	100	100	100	100
Yes	0.5	6.5	177	130	111	136	96
No	0.6	18.1	100	100	100	100	100
Yes	0.6	19.1	162	156	135	123	108

Kasai suggested that the effects observed after dry mixing may be due to one or more of the following reasons:

1. Shape of coarse aggregates is improved by dry mixing.

2. Old mortar which is attached to the surface of recycled aggregate particles is removed by dry mixing.

3. Fine particles of old cement which are liberated during dry mixing of recycled aggregates accelerate the hydration of fresh cement similar to a chemical agent.

In conclusion, dry mixing could improve the quality of recycled aggregate as it improves the shape of the aggregate particle and removes the attached mortar.

4.3.2 Coefficient of Variation of Compressive Strength of Recycled Aggregate Concrete

B.C.S.J (1978) and CUR (1986) found the coefficient of variation for compressive strength of recycled concrete in the laboratory not to be much different from that of conventional concrete when the same recycled aggregate was used throughout the production. When recycled aggregate concretes are produced from original concretes of different qualities, the coefficient of variation for compressive strength is much larger than when the same recycled aggregate is used in all batches. Typical results illustrating this point are presented by Hansen (1992) in table 4.13.

Table 4.13: Compressive Strength of one and the same recycled concrete produced with recycled aggregate from old concrete of different quality, (Hansen, 1992)

w/c Ratio of Original Concrete	Original Concrete When Crushed After 15 Years: Compressive Strength in MPa	w/c Ratio of Recycled Aggregate Concrete	Recycled Aggregate Concrete at 28 days: Compressive Strength in MPa
0.53	75.1	0.57	49.1
0.67	51.5	0.57	40.3
0.65	59.3	0.57	43.1
0.80	38.9	0.57	38.0
0.50	73.1	0.57	47.4
0.59	62.4	0.57	43.3
0.65	67.9	0.57	41.8
0.81	42.1	0.57	32.0
0.50	61.9	0.57	39.8
0.50	84.8	0.57	36.8
0.53	73.4	0.57	44.0
0.50	64.1	0.57	35.2

From the above table, one can see variations in the 28-day compressive strength from 32.0 MPa to 49.1 MPa when concretes of identical mix proportions are produced with recycled aggregates from twelve 15-years old concretes of widely different quality. The mean compressive strength of all recycled concretes in the above table is 41 MPa, and the standard deviation is 5 MPa, giving a coefficient of variation of 12%.

4.3.3 Modulus of Elasticity, Damping Capacity and Stress-Strain Relationship

Due to the large amount of old mortar with a comparatively low modulus of elasticity which is attached to original aggregate particles in recycled aggregates, the modulus of elasticity of recycled aggregate concretes is always lower than that of corresponding control concretes made with conventional aggregates.

Frondistou-Yannas found up to 33% lower modulus of elasticity for recycled aggregate concretes made with coarse recycled aggregate and natural sand compared to the modulus of elasticity of corresponding control concretes made with conventional aggregates (Frondistou-Yannas, 1984).

Kakizaki *et al*. (Kakizaki, Harada, & Motoyasu, 1986) found the elastic modulus of recycled aggregate concretes to be 25% to 40% lower than for regular concrete, depending on the respective qualities of the original concrete and the recycled concrete. A minimum value for the modulus of elasticity of recycled aggregate concrete E, to be used in the design of structures made from such concrete can be calculated from equation 4.1 when the compressive strength of the recycled aggregate concrete $\mathbf{f_c}$, and the density $\boldsymbol{\alpha}$ of the concrete is known:

$$\mathbf{E_c = 2.1 \times 10^5 \times [\alpha / 2.3]^{1.5} \times \sqrt{(f_c / 200)}} \qquad \textit{(Equation 4.1)}$$

B.C.S.J (1978) reports between 10% and 30% lower modulus of elasticity of recycled aggregate concretes made with coarse recycled aggregate and natural sand, compared to the modulus of elasticity of corresponding original control concretes. When recycled aggregate concretes were made with coarse recycled aggregate and 100% fine recycled aggregate, the modulus of elasticity was 25% to 40% lower compared to the modulus of elasticity of corresponding original control concretes. The Japanese results are presented in figure 4.13.

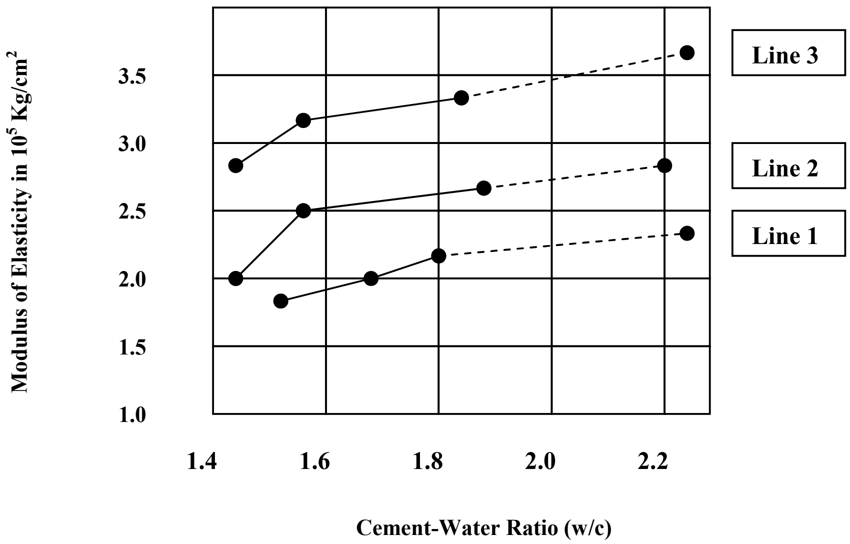


FIGURE 4.13: MODULUS OF ELASTICITY AS A FUNCTION OF W/C RATIO OF ORIGINAL AND RECYCLED AGGREGATE CONCRETE, (HANSEN, 1992)

***Notes on figure 4.13*:**

- Line 1: Cs – Cg = coarse and fine recycled aggregate.
- Line 2: Ns – Cg = natural sand and coarse recycled aggregate.
- Line 3: Ns – Ng = natural sand and natural gravel.

Hansen (1992) prepared one high strength (H: w/c = 0.40), one medium strength (M: w/c = 0.70), and one low strength concrete (L: w/c = 1.20) which were cured in water at 40ºC and tested for modulus of elasticity after 47 days.

The three concretes were passed via a laboratory jaw crusher. The crusher products were screened and recombined into three qualities of coarse recycled aggregate, H, M, and L, all of the same grading as the original aggregate. High strength, medium strength and low strength concretes will all form nine possible combinations of coarse recycled aggregates. All nine concretes were cured in water at 40ºC and tested for modulus of elasticity after 47 days of curing in water at 40ºC. From table 4.14, it is seen that both dynamic and static modulus of elasticity are from 14% to 28% lower for recycled aggregate concretes than for control concretes made with the same conventional aggregate. However, it is evident that differences in modulus of elasticity would have been much larger if the high strength concrete (H) has been made with a stiffer aggregate and the low strength concrete (L) had been made with a softer aggregate than the natural aggregate which was actually used in the experiment. In one case, Hansen found the modulus of elasticity of a recycled aggregate concrete which was made with recycled aggregate that consisted of a low quality crushed mortar to be 45% lower than the modulus of elasticity of a corresponding control concrete made with conventional aggregates.

Table 4.14: Static and Dynamic Modulus of Elasticity of Original and Recycled Aggregate Concretes after 47 days of accelerated curing, (Hansen, 1992)

Type	Modulus of Elasticity of Original & Recycled Aggregate Concretes, GPa											
	H	**H/H**	**H/M**	**H/L**	**M**	**M/H**	**M/M**	**M/L**	**L**	**L/H**	**L/M**	**L/L**
Dynamic Modulus	46.7	40.3	37.6	39.1	42.3	36.4	35.8	35.0	36.6	31.0	28.8	28.0
% Reduction below controls	0	13.7	19.5	16.3	0	13.9	15.4	17.2	0	15.3	21.3	23.4
Static Modulus	43.4	37.0	36.3	34.8	38.5	33.0	32.0	30.0	30.8	27.5	22.3	22.6
% Reduction below controls	0	14.7	16.4	19.8	0	14.3	16.9	22.1	0	10.7	27.6	26.5

** Where: H, M and L indicate original high strength, medium strength and low strength concretes made with natural gravel. H/M indicates high strength recycled concrete made with coarse aggregate produced from medium strength concrete, etc.*

On the other hand, Hansen reported that it was found that the ultimate strain at compressive failure to be 2.6×10^{-3} for recycled aggregate concrete made with both coarse and fine recycled aggregate while it was 1.7×10^{-3} both for an original control concrete and for a recycled aggregate concrete made with coarse recycled aggregate and natural sand.

Ravindrarajah and Tam found the damping capacity expressed in terms of the logarithmic decrement to be between 16% and 23% higher for recycled aggregate concrete than for conventional control concretes made with virgin aggregates. The damping capacity for both types of concrete increased with the decrease in compressive strength (Ravindrarajah & Tam, 1985).

In conclusion, the results obtained for recycled aggregates show that the modulus of elasticity is lower (20% to 40%) than conventional concrete most of the time and this might be due to the mortar attached to recycled particles. For the damping capacity, results show that recycled aggregate has higher damping capacity within 16-23%.

4.3.4 Creep, Drying Shrinkage, Tensile, Flexural and Fatigue Strength

Schulz (Schulz, 1986) found the creep of two recycled aggregate concretes, made with coarse recycled aggregate and natural sand, to be 50% higher than creep of the corresponding control concretes made with conventional natural and crushed aggregates (see figure 4.14).

Ravindrarajah and Tam (1985) stated that the creep of recycled aggregate concrete made with coarse recycled aggregate and natural sand was found to be 30-60% higher than creep of conventional control concrete. On the other side, CUR (1986) found creep of recycled aggregate concretes to be 25% and 45% respectively higher than for comparable natural aggregate concretes with compressive strengths of approximately 50 MPa and 25 MPa.

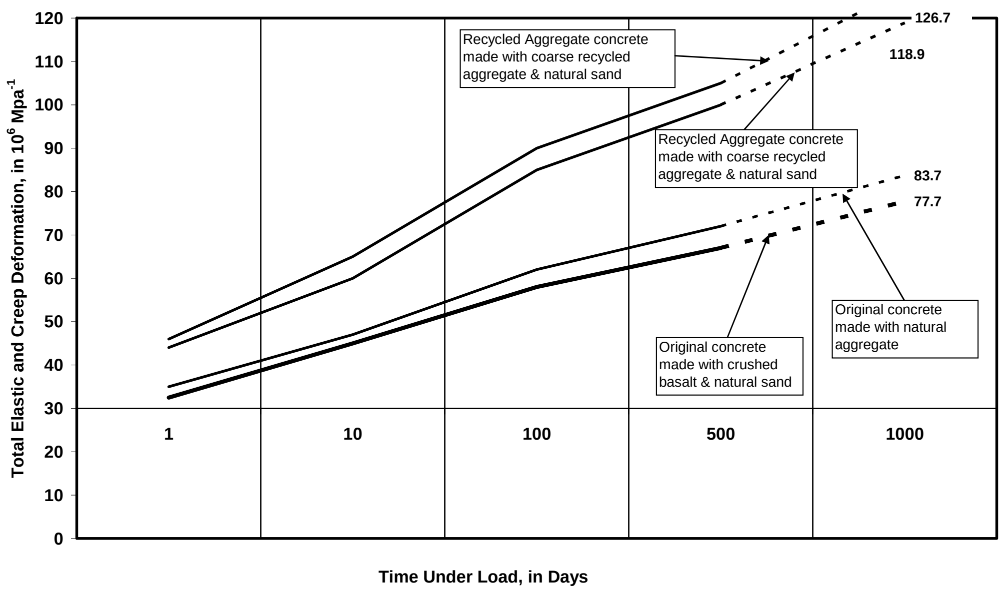


FIGURE 4.14: TOTAL DEFORMATION OF ORIGINAL AND RECYCLED CONCRETES (PER MPA) VERSUS TIME UNDER LOAD IN DAYS, (HANSEN, 1992)

Concerning the drying shrinkage, Hansen (1992) reports drying shrinkage of recycled aggregate concrete (Ns-Rc) made with a cement content of 300 kg/m3, with coarse recycled aggregate (Rc), and with natural sand (Ns) to be 50% larger than drying shrinkage of original concrete (Ns-Ng) made with natural sand (Ns) and natural coarse aggregate (Ng). When both coarse (Rc) and fine (Rs) recycled aggregates were used, drying shrinkage of recycled aggregate concrete (Rs-Rc) was 70-80% larger than that of a control concrete (Ns-Ng) made with natural fine and coarse aggregate (see figure 4.15).

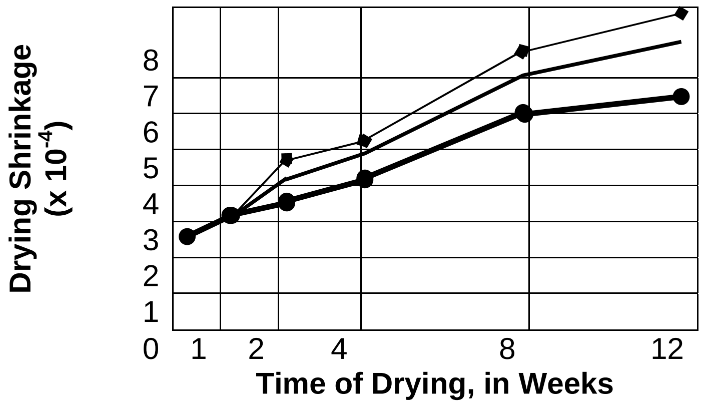
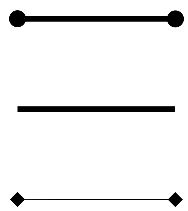


FIGURE 4.15: DRYING SHRINKAGE OF ORIGINAL AND RECYCLED AGGREGATE CONCRETES AS A FUNCTION OF TIME OF DRYING, (HANSEN, 1992)



Ns-Ng = Natural Sand & natural gravel

Ns-Cg = Natural Sand & coarse recycled Aggregate

Cs-Cg = Fine & coarse recycled aggregate

Hansen and Narud (1983) also reported their results for the drying shrinkage in table 4.15. It is seen from the table that the drying shrinkage of all recycled concretes (except for one erratic result for L/M) was approximately 50% higher than for corresponding control concretes made with the same conventional aggregates, regardless of mix proportions and type of recycled aggregate used. As a result, it might be concluded that drying shrinkage of recycled aggregate concrete made with coarse recycled aggregate and natural sand is approximately 50% higher than shrinkage of corresponding control concretes made with conventional aggregate. When both coarse and fine aggregates are used, drying shrinkage of recycled aggregate concrete is somewhat higher than shrinkage of corresponding control concretes made entirely with conventional aggregates.

Table 4.15: Shrinkage after 13 weeks of drying at 40% RH and 25ºC of original and recycled aggregate concretes, (Hansen, 1992)

Type	Shrinkage after 13 weeks of drying at 40% RH & 25ºC of original & recycled aggregate concretes											
	H	**H/H**	**H/M**	**H/L**	**M**	**M/H**	**M/M**	**M/L**	**L**	**L/H**	**L/M**	**L/L**
Total Shrinkage x 10^4	3.4	5.1	4.9	5.3	3.5	4.9	5.3	5.2	4.5	6.8	5.7	6.8
% Increase in Shrinkage above controls	0	50	44	56	0	40	51	49	0	51	27	51

** Where: H, M and L indicate original high strength, medium strength and low strength concretes made with natural gravel. H/M indicates high strength recycled concrete made with coarse aggregate produced from medium strength concrete, etc.*

Mulheron found that the irreversible shrinkage of concretes, subjected to complete drying and then wetting to saturation, are almost independent of aggregate type. However, the reversible shrinkage of the recycled aggregate concretes was generally higher than those of the controls (Lindsell & Mulheron, 1985).

When one speaks about the tensile, flexural, shear and fatigue strengths, B.C.S.J (1978) and Ravindrarajah and Tam (1985) found the indirect tensile, so-called 'cylinder splitting strength' of recycled aggregate concrete made with coarse recycled aggregate and natural sand not to be significantly different from that of conventional concrete. However, when both coarse and fine recycled aggregates were used, the tensile strength of recycled aggregate concretes was down to 20% lower than that of conventional concrete.

B.C.S.J (1978) found that the flexural strength of recycled aggregate concrete is somewhere between 1/5 and 1/8 of its compressive strength. Ravindrarajah and Tam (1985) found no significant differences in flexural strength of conventional concrete and recycled aggregate concrete made with coarse recycled aggregate and natural sand. However, they reported that both tensile and flexural strength of recycled aggregate concrete is consistently 10% lower than for natural aggregate concrete.

Hansen (1992) reported that reductions in strength caused by the use of coarse recycled concrete aggregate are approximately 6% for tensile strength, 0% for flexural strength and 26% for shear strength compared to corresponding strengths for ordinary concretes. He also reported that the flexural fatigue strength of concretes made with natural sand and coarse recycled aggregates was higher than that of comparable natural aggregate concretes.

In conclusion, the creep deformation and the drying shrinkage are usually 50% higher than that of original concrete. The tensile and flexural strengths are almost 10% lower than for original concrete.

4.3.5 Reinforced Concrete

Hansen (1992) reported that the bond strength between steel and recycled aggregate concrete is almost equivalent to that of conventional concrete under static and fatigue loading, when coarse recycled aggregates are used with natural sand. However, when both fine and coarse recycled aggregates are used, cracks appeared at 15% lower flexural load than when conventional aggregate was used, and the ultimate flexural strength of reinforced concrete was 30% lower due to bond failure. Shear strength followed a similar pattern.

It could be concluded that coarse recycled aggregate can be used in reinforced concrete without much inconvenience, but that fine recycled aggregate should be avoided. It appears that up to 30% of natural coarse aggregate or crushed stone can be replaced by coarse recycled aggregate without any negative effects at all (Hansen, 1992).

In conclusion the bond strength between steel and recycled aggregate concrete is almost the same to the case of conventional concrete when using coarse recycled aggregate and 100% natural sand. However, when fine recycled aggregate is used, the bond strength is reduced by 30%.

4.4 Durability of Recycled Aggregate Concrete

4.4.1 Permeability and Water Absorption

The rate of most kinds of concrete deterioration relies on concrete permeability. This is because water absorption is indirectly related to permeability of hardened concrete, and penetration of water into concrete is required for most deterioration mechanisms to be effective.

Kasai reports that B.C.S.J conducted water permeability tests on concretes which were made with water-cement ratios of 0.5-0.7 and with slump values around 21 cm. The results showed that the water permeability of recycled aggregate concrete is 2-5 times that of conventional control concretes (Kasai, Hisaka, & Yanaga, 1986).

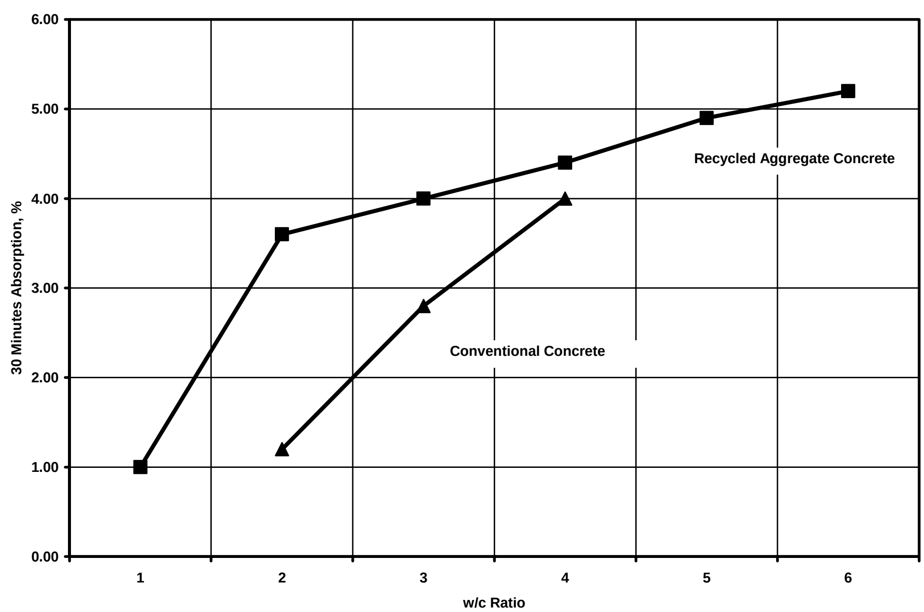


FIGURE 4.16: THIRTY MINUTES WATER ABSORPTION FOR RECYCLED AGGREGATE CONCRETE AND CONVENTIONAL CONCRETES MADE WITH DIFFERENT W/C RATIOS, (KASAI, HISAKA & YANAGA, 1986)

In conclusion, water absorption rates are higher for recycled concrete aggregates than in the case of conventional concrete by at least two times.

4.4.2 Carbonation and Reinforcement Corrosion

B.C.S.J (1978) found that the rate of carbonation of a recycled aggregate concrete made with recycled aggregate from an original concrete which had already suffered carbonation was 65% higher than that of a control concrete made with conventional aggregate. Also it reported that new concrete, produced from recycled coarse aggregate which has been produced from old chloride contaminated concrete in many cases would fail to meet current recommended limits for chloride ion in concrete. Use of fine recycled aggregate with coarse recycled aggregate might increase the risk of reinforcement corrosion in the new recycled aggregate concrete.

In conclusion, carbonation and reinforcement corrosion rates are higher for recycled aggregate concretes and they should be taken care of in the best manner.

4.5 Mix Design of Fresh Recycled Aggregate Concrete

In principle, mix design of recycled aggregate concrete is no different from mix design of conventional concrete, and the same mix design methods can be used. In practice slight modifications are required.

Assuming for example that one were to use for design of recycled aggregate concrete mixes, the DOE method (Teychenne, Franklin & Erntroy, 1975), which is widely employed in the UK. In that case, the following modifications would be appropriate.

1. In order to determine a target mean strength on the basis of a required characteristic strength, a higher standard deviation must be employed when designing a recycled aggregate concrete made with recycled aggregates of variable quality than when recycled aggregate of uniform quality or conventional aggregate is used.
2. At the design stage, it may be assumed that the free water-cement ratio for required compressive strength will be the same for recycled aggregate concrete

as for conventional concrete when coarse recycled aggregate is used with natural sand. If subsequent trial mixes show that the compressive strength is lower than assumed, an adjustment of the water-cement ratio must be made.

3. It can be assumed that for the same slump, the free water requirement of recycled coarse aggregate concrete is 10 l/m^3 higher than for conventional concrete.
4. A maximum recycled aggregate size of 16-20 mm may be required for reasons of durability.
5. Because of a higher free water requirement of recycled concrete mixes, the calculated cement contents will be somewhat higher for recycled aggregate concretes than the cement contents for corresponding conventional concretes.
6. Mix design must be based on the measured density of recycled aggregate at hand.
7. When estimating the ratio of fine to coarse aggregate, it can be assumed that the optimum grading of recycled aggregate is the same as for conventional aggregate.
8. It is imperative that trial mixes should be made in order to adjust the free water content necessary to attain the slump required, the free water-cement ratio necessary to attain the strength required, and the ratio between fine and coarse aggregate necessary to achieve the best economy and cohesion of the fresh mix. Larger deviations from values estimated according to the original DOE method can be expected for recycled aggregate concretes than for conventional concretes.

4.6 Products, Codes, Standards and Testing Methods for Recycled Aggregate Concrete

Lindsell and Mulheron (1985) have reviewed the wide range of aggregate products that can be manufactured depending on the type of demolition debris being processed and the capabilities of the recycling plant. For the purposes of comparison it is possible to classify this range of products into four main categories.

(i) Crushed Demolition Debris – mixed crushed concrete and brick that has been screened and hand-stored to remove excessive contamination, but still contains a proportion of wood and other impurities.

(ii) Clean Graded Mixed Debris – mixed, crushed concrete and brick which has been graded and contains little or no contaminants. It is suitable as general fill.

(iii) Clean Graded Brick – crushed and graded clean brick and masonry containing less than 5% other stony material and little or no contaminants. Stony material is used here to mean concrete, brick, natural stone and ceramic materials.

(iv) Clean Graded Concrete – crushed and graded clean concrete containing less than 5% brick or stony material and little or no contaminants. It is highly sought for fill and sub-base applications in drainage and road construction projects as it has sufficient hardness and durability.

Concerning the codes, standards and testing methods used for the recycled aggregate concrete worldwide, here is a list of these standards:

- In the USA: ASTM standards are being used.
- In Japan: the B.C.S.J 'Proposed Standard for the Use of Recycled Aggregate and Recycled Aggregate Concrete'.
- In the Netherlands: the Dutch concrete-code VBT 1986 by CUR.
- In the UK: the BS Guide 6543 'Use of Industrial by-products and waste materials in building and civil engineering'.

- In Russia: the 1984 N1IZbh of the Russian Research Institute for Concrete and Reinforced Concrete 'Recommendations on the recycling of sub-standard concrete and reinforced concrete products'.
- In Germany: the German standard DIN 4163.

However, still there are no specification limits for using recycled concrete aggregate in Egypt. Thus, a proposed specification limits table for some of the properties of recycled concrete aggregate has been developed in this study based on the researches and results that have been discussed in this chapter.

4.7 Properties of the Freshly Mixed Recycled Aggregate Concrete for the WALDSPIRALE Project

The lower dry density of recycled aggregate, when compared to natural dense aggregate, results in a higher absorptive capacity for water (RÜHL, 1997). This aspect was being specially considered in using consistency controlled concrete production. During rainy seasons the unsheltered recycled aggregate is very damp and generally completely water saturated. During sunny periods however, the aggregate is dry and can absorb water in the first 10 to 15 minutes during and after mixing, leading to a faster development of rigidity. To prevent this negative effect, the recycled aggregate was always dampened by sprinkling water over it during dry weather periods. In addition, the amount of cement paste was increased to compensate for the consistency loss due to the rough surface of the recycled aggregate.

These two alterations are necessary to produce a recycled aggregate concrete, which is equal to concrete made from natural dense aggregate regarding initial consistency, development of rigidity and compressive strength. Another positive aspect of the above alterations was a constant and substantially lower dosage of super-plasticizer at the construction site since the initial consistency was mostly invariant and the development of rigidity was more predictable than during the first building project "Vilbeler Weg".

The weekly checking of the recycled aggregate quality is also of great importance. In context with consistency controlled production, the grading curve of the aggregate mix is of substantial influence. During the construction phase of the "Waldspirale", the grading curve of all aggregate fractions remained within tolerable boundaries.

During construction, all concrete mixtures in use were tested. In this paper, only representative mixtures are shown. These were the two mixtures mostly in use:

- Concrete sort 590321 (B 25), the concrete for the foundations. Initial consistency was set to 36-38 cm in flow table value.
- Concrete sort 540423 (B 25), the concrete for all walls, ceilings, pillars, etc... Initial consistency was set to 40-42 cm in flow table value.

Both mixtures were designed by the guideline of the, Deutscher Ausschuss für Stahlbeton' (DAfStb, August 1988) and are displayed in Table 4.16.

Table 4.16: Main concrete Mixtures for the WALDSPIRALE Project, (DAfStb, 1988)

Concrete Sort	540423	590321
Compressive strength class	B25	B25
Water [kg/m^3]	190	180
CEM I 42,5 R [kg/m^3]	-	290
CEM III/A 32,5 R [kg/m^3]	300	-
Fly ash	50	40
Effective water-cement ratio[-]	0,59	0,59
Sand 0/2a [kg/m^3]	616	615
Aggregate 2/8 [kg/m^3]	530	290
Recycled aggregate 8/16 [kg/m^3]	569	334
Aggregate 16/32 [kg/m^3]	-	544
Water reducing agent [kg/m^3]	1,5	-
Initial consistency a_{10min} [cm]	40-42	36-38

Viewing the results of the 10 minute and 45 minute flow table tests (Table 4.17) it is obvious, that the consistency control method is applicable after a short optimization and acclimatization phase when starting the concrete production. All concrete mixtures were produced with the initial consistency set during the first laboratory tests (when comparing the mean value to the postulated a_{10min}). Concrete sort 540423 was initially produced slightly stiffer (a_{10min} = 38 cm; until 19th of January 1999) for safety reasons but then adjusted to a_{10min} = 42 cm when it was obvious that the concrete mixture would easily reach the estimated compressive strength, thus improving workability and reducing the super-plasticizer dosage on site. Sort 540423 was specially designed for winter construction and fast stripping, the main reason for the high compressive strength (postulated f_s=40N/mm).

The standard deviation of the flow table test value between 2.0 cm and 3.4 cm shows, that the consistency was held relatively constant during the whole construction period. The development of rigidity (a = a_{10min} - a_{45min}) is the same, as in the production of concrete with natural dense aggregate.

Table 4.17: Results of the consistency tests for the WALDSPIRALE Project, (DAfStb, 1988)

Concrete Sort	540423 until 19.1.99	540423 after 21.1.99	590321
Postulated a_{10min} [cm]	38-40	40-42	36-38
a_{10min} [cm]			
Meanvalue	38,3	41,2	36,3
Standard deviation	3	3,5	3,4
$a_{45minutes}$ [cm]			
Meanvalue	34,1	35,7	33,7
Standard deviation	2,1	2,9	3,2
Difference Δa [cm]	4,2	5,5	2,6

The average development of rigidity lies between 2.6 cm and 5.5 cm. The concrete mixtures produced with a stiffer initial consistency show a lower development of rigidity. The data collected from concrete sort 540423 shows the influence of a change in initial consistency: raising initial consistency from 38 cm to 42 cm increased the mean value for development of rigidity (a) from 4.2 cm to 5.5 cm.

4.8 Properties of the Hardened Recycled Aggregate Concrete for the WALDSPIRALE Project

The results of the compressive strength at the mixing plant tests show (Table 4.18), that all concrete sorts reach their destined class or even turn out better than expected. Since concrete sort 540423 was redefined during construction, the results before and after the redefinition were evaluated separately. The mean value for compressive strength of 52.34 N/mm^2 was much higher than needed; therefore it was decided to increase workability by adding more water to the mixture. This reduced the mean value to 42.29 N/mm^2. The values of the construction site test cubes were similar, 49.78 N/mm^2 before and 41.33 N/mm^2 after changing the initial consistency. The standard deviation of compressive strength is in an acceptable area, but is larger for concrete sort 540423 due to the fact, that often only very small amounts (approximately 10 m^3) were produced during one day. The sort 590321 was used for the foundations and was produced in greater daily amounts, therefore making it easier to optimize the consistency control method. This resulted in a smaller standard deviation of compressive strength compared to all other mixtures in use (Table 4.18).

Table 4.18: Results of the compressive strength tests for the WALDSPIRALE Project, (DAfStb, 1988)

Concrete sort	540423 until 19.1.99	540423 after 21.1.99	590321
Postulated f_s [N/mm^2]	40	40	30
Mixing plant			
Mean value [N/mm^2]	52,34	42,29	34,23
Standard deviation [N/mm^2]	4,35	4,44	2,44
Amount of cubes tested	69	213	57
On site			
Mean value [N/mm^2]	49,04	40,75	36,87
Standard deviation [N/mm^2]	5,28	4,36	3,53
Amount of cubes tested	66	196	51

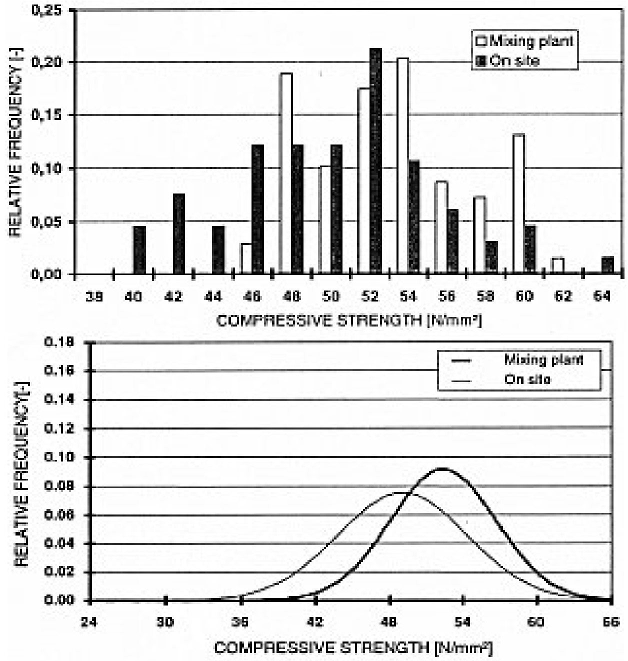


FIGURE 4.17A: HISTOGRAM OF COMPRESSIVE STRENGTH FOR THE WALDSPIRALE PROJECT, 540423 UNTIL 19.1.1999, (DAFSTB, 1988)
FIGURE 4.17B: GAUSSIAN DISTRIBUTION OF COMPRESSIVE STRENGTH FOR THE WALDSPIRALE PROJECT, 540423 UNTIL 19.1.1999, (DAFSTB, 1988)

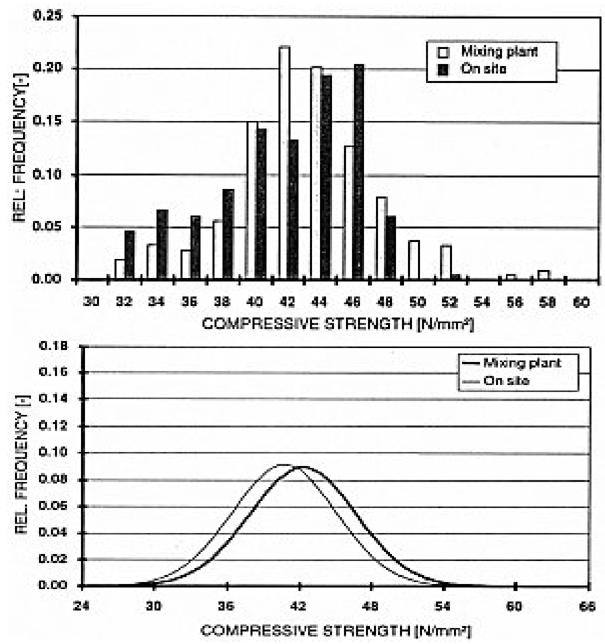


FIGURE 4.18A: HISTOGRAM OF COMPRESSIVE STRENGTH FOR THE WALDSPIRALE PROJECT, 540423 AFTER 21.1.1999, (DAFSTB, 1988)
FIGURE 4.18B: GAUSSIAN DISTRIBUTION OF COMPRESSIVE STRENGTH FOR THE WALDSPIRALE PROJECT, 540423 UNTIL 21.1.1999, (DAFSTB, 1988)

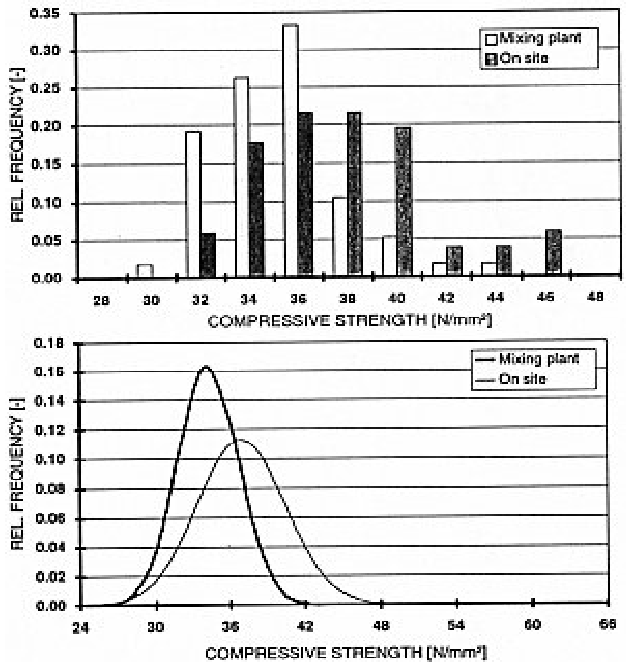


FIGURE 4.19A: HISTOGRAM OF COMPRESSIVE STRENGTH FOR THE WALDSPIRALE PROJECT, 590321, (DAFSTB, 1988)
FIGURE 4.19B: GAUSSIAN DISTRIBUTION OF COMPRESSIVE STRENGTH FOR THE WALDSPIRALE PROJECT, 590321, (DAFSTB, 1988)

In general it is always of advantage to produce larger amounts of each concrete sort per day, as it was the case with sort 590321. Since the mixing plant produced concrete for one construction site only (namely the "Waldspirale"), the amounts of concrete called for only exceeded 200 m^3/day during the concreting of the foundations. This is not realistic, as a regular mixing plant serves for more than one construction site. It is therefore obvious, that the optimization process will be of even greater success in industrial scale production (RÜHL, 1997).

4.9 Conclusions for the WALDSPIRALE Project

Concrete made with recycled aggregate can be used in many areas up to compressive strength class B35 according to the DAfStb guideline (RÜHL, 1997). After applying the mentioned two measures in the production process, concrete with recycled aggregate shows no relevant difference to concrete made from natural dense aggregate and can be cast or pumped just like a standard concrete mixture. The addition of super-plasticizer before dusting is only necessary, if the concrete is produced with a stiffer consistency as demanded by the contractor on site, as it was the case with the "Waldspirale". The reason for this was to minimize hydration temperature by limiting the amount of cement paste and gaining workability with super-plasticizer. For building members which are not susceptible to hydration temperature development, the necessary workability consistency can be achieved by controlling development of rigidity (by dampening the recycled aggregate) and initial consistency (by increasing the amount of cement paste) alone.

In conclusion, recycled aggregate concrete can perform in the same manner as conventional concrete provided that more care is given to quality control.

4.10 Results of Recycled Aggregate Concrete for the "WETLAND PARK"

Based on the specifications of Hong Kong mentioned in chapter 2, the replacement levels of recycled coarse aggregate for the "WETLAND PARK" were 100% and 20% for concrete grades C20 (or below) and C25 to C35, respectively. Because of the limited experience in using recycled aggregates in concrete in Hong Kong, at the beginning of the project, the cement contents for the concrete mixes were deliberately increased by around 4% to compensate for the higher initial free water content required by the recycled aggregates so as to maintain a similar water/cement ratio.

The statistical results listed in Table 4.19 show that the average 28-day cube strength and the standard deviation of recycled aggregate concrete used in the project were about the same as those of ordinary concrete. The similar standard deviations show that the quality of concrete using recycled aggregates can also be controlled to a similar stability as that of ordinary concrete.

Table 4.19: Statistical Results of Recycled and Natural Aggregate Concretes for the Wetland Project in Hong Kong, (Hong Kong Polytechnic University, 2006)

Concrete Grade	Slump (mm)	RA (%)	Cement (kg/m^3)	w/c	28-day cube strength (MPa)	SD for running 40 samples
C35	100	20	395	0.466	47.3	2.8
C35	100	0	380	0.473	48.2	4.1
C35	75	20	380	0.468	47.1	4.8
C35	75	0	365	0.479	45.8	4.5
C30	75	20	360	0.486	44.7	4.4
C30	75	0	345	0.507	42.1	4.7
C20	75	100	300	0.607	31.4	5.0
C20	75	0	290	0.603	32.8	4.4

In Hong Kong, most concrete batching plants were originally designed and built for concrete production with virgin aggregates only. In order to accommodate the recycled coarse aggregate, additional storage compartments had to be installed with all the necessary feeding and batching accessories (Hong Kong Polytechnic University, 2006).

Also, as the water absorption rate of recycled aggregates was much higher than that of virgin aggregates, and to avoid excessive slump loss, the recycled aggregates were required to be pre-wetted both at the stockpiles of the recycling plant and by sprinkling water mist on the recycled aggregates during unloading at the receiving hopper at the batching plant before feeding to the overhead bin.

The moisture content in the recycled aggregate was then compensated during the mix design. Chemical admixtures that would facilitate good workability retention were also added. But soft materials such as old cement mortar that were originally adhered to the old aggregates were quite easily broken off during mixing of the concrete which further contributed to the slump loss. The slump of the concrete produced therefore tended to be rather unstable, although the performance could still be controlled within the limits of acceptance. Also, the rate of slump loss was high which meant the workable time of the concrete was also reduced. As such, when recycled aggregates are used in ready mixed concrete production, it is advisable to adopt a higher initial design workability to compensate for the higher anticipated slump loss (Hong Kong Polytechnic University, 2006).

4.11 Conclusions for the "WETLAND PARK"

Hong Kong is running out of both reclamation sites and landfill space for the disposal of construction and demolition materials/waste. It is important for Hong Kong to adopt a strategy to reduce and recycle C&D materials/waste and handle it in a more environmentally responsible way. Recycled aggregates have been demonstrated to be able to produce quality concrete for structural applications. More research and development would be needed to further promote the recycling concept and widen the scope of applications of recycled aggregates.

In conclusion, recycled aggregates could perform quite well and the high water absorption rates could be controlled by pre-wetting. Also chemical admixtures could facilitate good workability for recycled aggregates.

4.12 General Conclusions for the Production and Properties of Recycled Concrete Aggregate

The following conclusions could be deduced:

- Plants for production of recycled concrete aggregates are not much different from plants for production of crushed aggregate from other sources.
- There are two mechanisms of crushing. One is the closed system which has the advantage of limiting the maximum size of aggregate particle. The second is the open system which has larger capacity than the closed system but it has a disadvantage where the maximum aggregate particle size is not well defined.

- There are four types of crushers developed. The first is the jaw crusher which produces the best grain size distribution for recycled aggregate. The second is the cone crusher which is usually used as a secondary crusher as it has a maximum of 200mm feed size. The third is the swing hammer crusher which is seldom used, and the fourth is the impact crusher which is mostly used for roads construction as it is less sensitive to materials that can hardly be crushed.
- Grading and particle shape: Fine recycled aggregates are not preferred as they are coarser and more angular than that desired for the production of quality concrete. On the other hand, the coarse recycled aggregates have shown satisfactory results and they are almost similar to conventional coarse aggregates.
- Water Absorption and Permeability: High porosity due to high mortar/cement paste content.
- Density: Crushed concrete will have a bulk density somewhere in-between rock materials and light weight aggregate.
- Los Angeles Abrasion, BS Crushing value and BS 10% fineness value: recycled concrete aggregates are expected to pass the standard limits of ASTM C33 and BS 882.
- Sulfate Soundness and Chlorides: Durability aspects should be controlled. Different results were obtained from various scientists. More investigations are needed for this area.
- Contaminants: There is a risk for contamination of organic compounds, heavy metals and other environmental hazardously substances, for example from traffic and chemical industries. Glass and gypsum plaster are the most critical contaminants. Much care should be given to these two contaminants.

- Compressive Strength: Depends mainly on the strength of the original concrete being recycled and also controlled by the w/c ratio of the recycled concrete. Results have shown that coarse recycled aggregate might lead to a similar compressive strength of concrete when compared to conventional aggregate. This is achieved when using 100% natural sand with the recycled coarse aggregate. On the other hand, fine recycled aggregates might lead to a reduction in the compressive strength within a range of 10-40%.
- Modulus of Elasticity: Lower than in the case of conventional concrete within a range of 20-40%.
- Creep deformation and Drying Shrinkage: Higher than in the case of conventional concrete.
- Tensile and Flexural Strength: Almost 10% lower than the case of conventional concrete.
- Reinforced Concrete: Bond strength between steel reinforcement and recycled aggregate concrete is almost similar to that of conventional concrete when using coarse recycled aggregate with 100% natural sand. However, when using fine recycled aggregate, bond strength might be up to 30% lower than in case of conventional concrete.

CHAPTER 5
ENVIRONMENTAL, ECONOMIC AND MANAGEMENT CONCERNS

From the survey results, it was deduced that some of the main reasons behind the absence of the application of concrete recycling in Egypt are the environmental and economic and the absence of management models for recycling. This chapter aims to tackle the environmental and economic concerns in recycling of concrete and present a management plan in order to be guidance for the recyclers.

5.1 Environmental Aspects in Recycling

5.1.1 Environmental Concerns

Recycling of concrete aggregate presents both environmental advantages and disadvantages. The advantages are that substances are reused which would otherwise be classed as waste; reduction of fuel use, reduction of trucking, and reduction of the use of non-renewable resources. The disadvantages include the intrusion of trucking into locations where this is undesirable; aesthetic concerns, and potential noise and dust control problems (Hansen, 1992).

Operation of a crushing and screening plant is always accompanied by the generation of noise, vibrations and dust. Therefore, in the selection of plant location, environmental conditions of the vicinity and legal requirements must be carefully studied and necessary counter-measures taken. However, the early concern about noise and dust problems when crushing concrete in mobile plants in urban areas has apparently been exaggerated.

Hansen (1992) stated that Dierkes reported on a mobile plant which was set up near a local commercial and residential area in Chicago, Illinois. The only complaints received concerned night-time operations, the banging of tailgates to clean trucks, and the noise from back-up alarms on mobile equipment. Such practices were stopped, and stockpiles and earth beams were built around the perimeter to reduce the noise. The hoppers of the primary crushers were lined with rubber pads to reduce the impact noise, diesel generator engines were equipped with quieter mufflers, and sound absorbing panels were placed around the generator trailers.

Also Hansen mentioned (1992) that Copple reported on a crusher which was set up on a busy urban street in a suburb of Grand Rapids, Michigan, where no complaints were received about either dust or noise from the plant.

Environmental concerns in recycling of concrete are discussed by Hansen (1992) who concludes:

- Single purpose job site installations, for example for the purpose of recycling a pavement, is easier to located than a permanent commercial type installation, but a permanent site has the advantage of being able to recycle slabs and footings from building demolition as well as pavement.
- To recycle the aggregates into concrete, the best location of a permanent plant is adjacent to a ready-mixed concrete batch plant in an area of heavy industrial zoning. The recycling plant should be located on a road which is already used for heavy commercial or industrial trucking. Once located, there must be sufficient control exercised over the trucks to ensure that they are always using acceptable heavy duty roads.
- Emission of dust should be limited. The easiest control of dust is water. Roads around the site should be continuously watered as should the stockpiles of broken concrete. Fine mist water should be used at the crusher feed and screens. This spray must be very fine or the material will be too wet and the fine screens will blind.
- Personnel noise exposure should be limited to 90 decibels for an 8-hours day. In the case of front-end loaders, bulldozers and the like, this can be done by

installing noise attenuated cabs. Plant operators can likewise have well-located enclosed operating positions. Personnel which must be around the plant during operation must be protected either by administrative or engineering controls.

- Community noise, i.e. noise at the receiving property, should be limited to no more than 55 decibels for daytime hours or 50 decibels during the evening. The simplest way of controlling noise is distance. Noise impact will be reduced by 6 decibels for each doubling of the distance.

Kakizaki M., Harada M. and Motoyasu have studied the noise levels of different crushing machines. They stated that in city areas the noise levels ought to be lowered below those regulated by current noise control regulations by means of acoustic barriers of various kinds, or complaints are certain to be received (Kakizaki, Harada, & Motoyasu, 1986).

It may be concluded that the only way an operator of a recycling plant can be certain that his products will be free from dangerous contaminants is to make sure that the contaminants do not get in there in the first place. Such certainty can only be attained by refusing any demolition debris which is contaminated with (impregnated) wood, paper, plastics, textiles, cables, non-iron metals, steel (except for small amounts of reinforcing steel), soil and clay, domestic or industrial waste, gypsum, and other deleterious mineral products, oil, grease, rubber or components which in any way are contaminated by chemicals. This poses a responsibility on the individual operator, and it forces the demolition contractor to carry out selective demolition at least to a certain extent. Moreover, it increases the cost of processed demolition waste, thus severely restricting the quantities that can be recycled. Therefore, authorities should make certain that their requirements are justified, which is not always the case.

As a summary, the location of the recycling plant, the operation noise and dust are the major environmental concerns in recycling that should be well considered.

5.1.2 Environmental Regulations for Construction Waste Disposal in Egypt

As mentioned before, the amount of wastes produced by the construction industry in Egypt amounts to 10,000 tons per day which is equivalent to one third of the domestic solid wastes produced in Egypt (El-Haggar, 2004) whereas the construction wastes represent 25% of the total domestic solid wastes produced in the United States.

Most of the demolition contractors in the developing countries dispose of these wastes by storing them on sides of the roads or in some general dumping areas and this is attributed to the fact that there are almost no recycling plants in most of these countries.

The Egyptian Environmental Protection Law number 4 for year 1994 has determined the procedures that should be taken in clauses 39 and 41 and they are as follows:

1- Safe storage should be followed in order not to hinder the traffic motion and wastes should be covered to avoid air pollution.
2- Wastes should be transported in special containers and the trucks should have the following specifications:
    - To be equipped with a special container or well fitted cover to avoid dust from spreading in air.
    - To be equipped with special loading and unloading tools.
    - To be in good condition as per traffic law requirements.
3- The dump areas should be away from residential areas by not less than 1.5 Km with a lower contour level.

4- Dump areas should be determined only by the municipalities.

El-Haggar (2004) has also provided some guidelines for managing the wastes produced from the construction industry as follows:

- Stage 1: Planning and Analysis.
- Stage 2: Documentation of planning phase.
- Stage 3: Execution.
- Stage 4: Assessment after construction.

As a conclusion, the environmental concerns involved in recycling of concrete could be easily eliminated as long as the recycler copes with the regulations of the environmental law. Egypt has its own environmental law that could be used to minimize the environmental concerns.

5.2 Economic Aspects in Recycling

5.2.1 Economic Concerns in Recycling Concrete

Economic concerns in the recycling of concrete have been analyzed by Frondistou-Yannas (Frondistou-Yannas & Ng, 1977; Frondistou-Yannas, 1984; Frondistou-Yannas & Itoh, 1977) for what concerns the United States, by CUR in 1986 for what concerns the Netherlands, and by Drees in 1989 for Germany. The following conclusions can be drawn on the basis of these three studies. Conditions which are conductive to successful operation of recycled aggregate plants include:

- Abundant and constant supply of demolition rubble.
- High dumping costs for demolition rubble.
- Easy access for heavy trucks.
- Suitable industrial land available, preferably next to a sanitary land fill.
- Inaccessibility or scarcity, and therefore high cost of good quality natural sand and gravel or crushed stone.

- Ready market for products.

Considering these factors, it is not surprising that one of the largest recycling plants in the world is located in West Berlin (Hansen, 1992) and that densely populated countries such as parts of the United States, the Netherlands, Belgium, Germany and Japan are among the first to consider large scale recycling of demolition waste.

Pavement and runways present favorable cases for recycling of concrete because large quantities of relatively clean concrete rubble are generated over a short period of time. It is generated within a very limited area, and transportation along still existing parts of pavements present no problems. Moreover, such rubble can be processed in simple plants without washing or elaborate sorting and cleaning.

In almost all practical cases where concrete pavements or runways have been crushed and recycled, considerable savings have been achieved compared to the combined cost of dumping the old concrete and hauling in new base or sub-base material from pits and quarries or producing new concrete from conventional aggregates (Hansen, 1992). The largest savings have been achieved where conventional aggregate was locally unavailable, and for that very reason most of the recycling projects that have been carried out have been located in areas with storage of natural aggregates.

However, concrete used in streets and highways typically accounts for only about 15-20% of total concrete consumption in industrialized countries (Frondistou-Yannas & Ng, 1977; Frondistou-Yannas, 1984). In order to operate recycling plants at high capacities, thereby realizing economies of scale, the large quantities of concrete rubble generated from the demolition of old buildings, pavement, sidewalks, driveways, curbs, gutters, etc. are also required, and it must be processed into aggregate for production of new concrete which can be accepted by the construction industry as a reasonable alternative to conventional aggregate.

The economy of large-scale recycling of mixed concrete rubble in metropolitan areas is very much different from the economy of recycling of pavements and runways. For one reason it introduces the problem of contamination as the demolition rubble is mixed with gypsum, wood, plastics and steel which must be removed before the recycled product can be used for production of new concrete. Thus, much more elaborate plants are required to process mixed demolition rubble than clean concrete from highway pavements. A flow chart illustrating the design of a plant which is capable of producing concrete aggregate from mixed demolition debris is shown in figure 4.2 in chapter 4 of this study.

Economic Concerns in the USA

The macro-economics of plants capable of processing mixed concrete debris in the United States were studied by Frondistou-Yannas. Frondistou-Yannas found that a prerequisite for the economic justification of concrete rubble recycling is the presence of sufficiently large quantities of concrete debris so that a recycling plant of optimal size can be operated at high utilization factors. Accordingly, several researchers (Hansen, 1992) have assessed the quantities of concrete debris produced locally in the United States. It has been found that, on the average, 0.27 tons of concrete rubble (*in 1992*) per capita is generated each year in the United States (Hansen, 1992). It follows that in urban areas with a population greater than half a million people, the amount of concrete debris generated annually is of the order of a few hundred thousand tons. By contrast, a single highway demolition project produces only a few tons of thousand tons of debris.

On the basis of an economic analysis, Frondistou-Yannas found that in order to realize economies of scale, a plant should process at least 110-275 tons of debris per hour, and in order to produce a reasonable return on investment, the plant should process and sell no less than 200,000 tons of recycled aggregate per year. This implies that urban areas of at least one million people are needed to support the operation of a concrete recycling plant in the United States. There are no reasons to believe that this requirement would be substantially different in other industrialized countries.

Frondistou-Yannas suggests that for economical and other reasons that the most favorable location of a recycling plant would be at a fixed position near a large city, preferably next to a sanitary land fill so that trucks that bring in debris on their way back will carry aggregate. The adjacent sanitary land fill additionally reduces transportation costs as concrete contaminants do not have to be transported to a distant dump. Portable units should be used so that the plant can be relocated to a different site next to a new sanitary land fill when the capacity of the old fill is exhausted. However, recycled concrete aggregate can be sold only if it compares favorably with its competitor, natural aggregate (Hansen, 1992).

In conclusion, the most crucial economic concerns for recycling in the USA are the recycling plant location, the amount of debris available and the production capacity of the plant.

Economic Concerns in the Netherlands

CUR (1986) has analyzed economic aspects of recycling of concrete in the Netherlands and attempted to make a comparison between the two types of aggregate on the basis of two concrete members of equal performance, one made with recycled concrete aggregate and the other made with natural aggregate. Table 5.1 shows the main factors adding up to the total cost of recycled aggregates. CUR (1986) found that:

- The extra work on the demolition site which is required in order to prepare demolition debris for recycling is equivalent to 25% of the regular demolition costs (S_1).
- Dumping charges (S_2) depend very much on local circumstances. In the Netherlands in 1982, they varied from 3 Dfl (Dutch guilders) to 30 Dfl per m^3.
- The extra costs for preparation, processing, inspection, storage, and sale of recycled aggregates, S_7 = 12 Dfl, which appear in table 5.1 and later in table 5.2, are based on an average of estimates made in 1982 by a number of Dutch companies actually engaged in commercial processing and sale of recycled aggregate.

Table 5.2 gives the Dutch cost comparison between concretes of equal strength, produced with natural gravel and recycled concrete aggregate. All costs quoted are based on experiences from real productions in the Netherlands, and they are quoted in 1982 prices in Dutch guilders. Costs of transportation are assumed to be equal for all four concretes.

It is shown in table 5.2 that when dumping charges for demolition debris are left out of consideration, recycled building rubble was not competitive for concrete production in the Netherlands in 1982 as compared to natural gravel.

The 1982 market prices which are quoted in table 5.2 for recycled aggregates apply to rubble aggregates used as road-base materials. For such purposes, rubble aggregate is competitive because crushed natural rock which is required for road construction is more expensive than natural gravel. In 1982 nearly two million tons of demolition rubble were processed into recycled aggregates and used for un-stabilized road bases in the Netherlands. In order to be competitive for concrete production, it appears from table 5.2 that in the Netherlands, recycled aggregate would have to sell for approximately 25% less, instead of 50% more than natural gravel in order to compete with natural gravel for concrete production.

Table 5.1: Comparison of Cost Elements in the Processing and Handling of Natural Aggregates and Recycled Aggregates [Dfl = Dutch guilders], (Hansen, 1992)

<u>Natural Aggregates</u>	Dfl.	**<u>Re-Use of Rubble Granules</u>**	Dfl.
Excavation costs	N_1	Extra treatment of debris at the demolition site	S_1
Production costs (including interim storage)	N_2	Dumping charges (negative) for demolition debris	S_2
Bulk transport costs	N_3	Costs of transport of demolition debris to dump (negative)	S_3
Costs of transport to building site	N_4	Costs of transport of debris to processing plant	S_4
		Processing costs for recycled aggregate	S_5
		Costs of transport of recycled aggregate to building site	S_6
		Extra costs for inspection, storage, and sale of recycled aggregate	S_7
Total	ΣN_i	Total	ΣS_i
Requirements for recycled aggregate to be competitive provided the buyer is unbiased: $\Sigma S_i \leq \Sigma N_i$			

In 1982 recycled concrete aggregate produced by the only large scale plant in France at Limeil-Brevannes near Paris was selling at twice the cost of natural materials (Hansen, 1992).

Table 5.2: Cost Comparison between Concretes made with Natural Gravel, Recycled Concrete Aggregate, Brick Rubble, and Mixed Concrete and Brick Rubble Aggregate in the Netherlands (1982), (Hansen, 1992)

1. Natural gravel concrete with 180 kg of gravel at Dfl 22 per ton	Dfl 23.76 per ton
2. Concrete made with recycled concrete aggregate - 900 kg of recycled concrete aggregate (4-32 mm) at Dfl 17 per ton (production & processing costs)	Dfl 15.30 per ton
- 40 kg of cement at Dfl 125 per ton	Dfl 5.00 per ton
- Extra costs for inspection, storage, and sale at Dfl 12 per ton	Dfl 12.00 per ton
Total	**Dfl 32.30 per ton**

For comparison, Frondistou-Yannas found that in the United States recycled aggregates would have to sell for at least 50% less than natural gravel in order to compete on equal terms with natural gravel for concrete production. Even at this price an unprejudiced person would be indifferent to natural aggregate or recycled aggregate.

However, there are good reasons why a person could be prejudiced against recycled aggregate. For one, experience with its uncertainties remains concerning the performance of recycled aggregates in concrete. Secondly, extra costs and inconveniences are involved in the use of recycled aggregates for concrete production such as for example costs of pre-soaking, extra inspection, and costs for compensating for lower strength and higher creep, shrinkage, and elastic deformation of recycled aggregate concrete. Some of the costs may be offset by lowered density or better thermal insulation of recycled aggregate concrete. Even so, the price of recycled aggregates will have to come down in order for the material to be competitive with conventional aggregate. There are two ways in which this can come out:

- The extra cost of 12 Dfl per ton, which was charged in the Netherlands when the report was prepared for the processing of old concrete and building rubble into recycled aggregate, can be lowered once the initial developing phase is over. Already in 1982 this would have brought the price of recycled aggregate down to level where it would have been competitive with natural gravel provided the customer was unbiased.
- The price of conventional aggregates will continue to rise as raw materials get scarcer and transportation costs higher. More important, dumping charges for demolition debris are expected to rise steeply as the quantity of demolition debris and particularly that of concrete debris will continue to increase rapidly

throughout the coming years. Without crushing, concrete debris packs very poorly and tends to render sanitary fills unsuitable for future use as building sites.

All in all it can be expected that the use of recycled aggregate for concrete production will increase in the future as both the demand for road-base material and the price of recycled aggregate is foreseen to decrease in most industrialized countries (Hansen, 1992).

In conclusion, the most crucial economic concerns for recycling in the Netherlands include the uncertainties concerning the performance of recycled aggregates in concrete that might lead to extra costs for quality enhancement,

Economic Concerns in Germany

Drees (1989) found that in Germany one may count on the generation of 0.3 tons of demolition rubble (estimate at 1989) suitable for recycling per person per year. This makes for a total of 18 million tons per year. It is considerably less than what is assumed in the optimistic estimates which have been made by other researchers. Compared to a total yearly production of about 500 million tons of raw materials of mineral origin in Germany, 18 million tons are considered as a small part. However, it is significant, because demolition waste amounts to 2/3 by weight, or 1/4 volume of the total yearly deposits on city dumps. The costs of manually sorting the demolition waste would amount to 25 DM/m^3 (DM = Deutschmark) in 1989 prices. Mechanical sorting would reduce the costs to 8-10 DM/m^3 in 1989 prices.

At the present time, economical use of clean demolition rubble is only sensible for road construction or as fill. Use of crushed and cleaned demolition rubble as aggregate for production of structural concrete is not economically viable and probably not technically desirable because of its lower quality compared to conventional aggregates.

When building structures are demolished and it is desired to reuse the concrete, all components which contain deleterious materials such as wood, plastics, glass, lightweight materials and metals should be removed as far as this is economically possible before demolition of the load carrying structure itself.

After a thorough review of different lay-outs and equipment of recycling plants for demolition, Drees (1989) arrives at the conclusion that the total cost of a stationary plant itself would be 3.2-4.5 million DM according to the prices in 1989 without including the cost of real estate. This is considerably more than what has been assumed by others, but probably a realistic estimate. Mobile and semi-mobile plants would cost between 700,000 and 900,000 DM in 1989 prices according to Drees.

Production costs of marketable recycled demolition rubble depend on the required quality of the material produced. The least expensive is demolition rubble produced by a mobile plant on the demolition site, where the product is only intended for use as fill. The same is true for reuse of demolition rubble on site for road construction purposes. According to Drees production costs for such materials would typically be somewhat between 5 and 7 DM/ton in 1989 prices. For cleaned and processed building demolition waste produced to high quality requirements in stationary plants the costs would typically be 10-12 DM/ton and could rise to more than 15 DM/ton if the plant runs at lower than optimum capacity.

Charges for receiving demolition rubble at dumps, and sales prices for end products depend on local authorities. If there is a long distance to the nearest dump, high dumping charges of 8-11 DM/ton can be expected for reception of the rubble. If at the same time transport distances for virgin fill and aggregates are long, crushed and clean recycled materials can possibly be sold for 10 DM/ton in 1989 prices. Under less favorable conditions, charges for receiving demolition waste may be as low as 3-4 DM/ton and the sales price for processed material may have to be as low as 6-8 DM/ton. In order to breakeven, it is estimated that the difference between dumping charge and sales price should be at least 10 DM/ton for a stationary plant. For existing plants, this difference was frequently only 9-9.5 DM/ton in 1989. Thus, the processing of demolition rubble was not yet a profitable business in 1989 (Drees, 1989).

Drees is not in favor of government interference, but he does recognize that government regulation of dumping charges for demolition waste in heavily populated areas must be regulated if recycling plants are going to have a realistic chance to survive.

In conclusion, the most crucial economic concerns for recycling in Germany include the uncertainties concerning the performance of recycled aggregates in concrete that might lead to extra costs for quality enhancement.

Economic Benefits in Recycling

The National Science Foundation Building Case Study

The following case study discusses the economic benefits of using recycled aggregate concrete. This study presents the major findings of a wide-scale investigation that was supported by the "National Science Foundation" in the United States (Abou-Zeid, Shenouda, McCabe & El-Tawil, 2004). One of the main objectives of this study was to present cost items associated with an actual case in which recycled concrete is used in a small size job. The case study was performed on a five-story building in a semi-urban district and the decision was to be made on one of the following options for the new construction of the building. The site involved around 1,800 tons of coarse aggregate which is equivalent to 1,500 cubic meters of concrete.

The two main options, from which one option should be selected, were as follows:

A] Recycling the demolished concrete in order to be utilized for the new construction of the targeted building.

B] Using new virgin aggregate for producing new concrete.

Option A – Using the Recycled Aggregate Concrete to Produce the New Concrete

- ***Crusher*** (for crushing the demolished concrete):

  - Crushing capacity = 15 tons per hour.
  - Rental cost = 225 USD per day (including fuel & maintenance).
  - Assuming 8 working hours per day. Thus, the crusher could crush (15 tons per hour) x (8 hours per day) = 120 tons per day. Therefore, the 1,800 tons could be crushed at: (1,800 tons) / (120 tons per day) = 15 days.
  - Therefore, the total cost of the crusher for the crushing process = 15 days x 225 USD/day = **3,375 USD**.

- ***Operation and Handling***: a cost of **900 USD** is required.

- ***Quality Enhancement***: a cost of **2,750 USD** is required to account for the drop in quality of recycled concrete as opposed to conventional concrete.

- ***Transportation and Disposal***: a cost of **3,150 USD** is required for the transportation and disposal of other demolition waste materials.

Total Cost for Option A = 10,175 USD

Option B – Using Conventional Aggregate to Produce the New Concrete

- ***Crusher***: Not applicable in this option.

- **Transportation**: a cost of ***5,450 USD*** is estimated for transporting the waste materials to a dumping site located 30 Km from the project site.

- ***New Materials***: the cost of purchasing the new virgin aggregates delivered on site is 6.50 USD per cubic meter, i.e. 3.85 USD per ton. Thus, a total cost of 1,800 tons x 3.85 USD per ton = **6,930 USD** is estimated.

- ***Dumping Fees***: rate is equal to 1.5 USD per ton (without any taxes). Thus, a total dumping fees of 1.5 USD/ton x 1,800 tons = **2,700 USD** is estimated.

Total Cost for Option B = 15,080 USD

As a conclusion for the case study, option A was selected as it saved about 49%. Also, from this case study, one can conclude that:

- Transportation costs play a crucial role in determining the economic feasibility of the best scenario.
- The dumping fees, policies, taxies and/or levies can be useful tools for promoting the utilization of recycled concrete aggregate as they have cost implications.

5.2.2 Conclusions for the Economic Aspects in Recycling

In conclusion, one can summarize the economic concerns in recycling as follows:

- Plant capacity: a minimum of 110-275 tons per hour should be targeted for the recycling plant in order to meet the economies of scale.
- Cost Elements: the major cost elements involved in recycling include: the capital investment required, the operation costs, the land value, the extra treatment costs of the incoming waste, the transportation costs of the waste to the recycling plant, the transportation costs of the plant in case of mobile plants, the cost required for enhancing the quality of the end-product, and finally the transportation costs of the end-product to the construction site.

5.3 Management of Concrete Waste

Recycling of concrete waste can provide opportunities for saving resources, energy, time, and money for the Egyptian society. Furthermore, recycling and controlled management of concrete waste will save use of land and create better opportunities for handling of other kinds of waste. There are a number of opportunities for utilization of concrete waste apart from dumping. Recycling of concrete can be accomplished by: reuse of concrete products, processing into secondary raw materials for use as fill, road bases and sub-bases, or aggregate for production of new concrete.

The prospect of using concrete waste depends on a range of factors related to the building and construction industry, and to the consumption of resources and energy, where the main three factors are: population density, occurrence of and access to natural materials, and level of industrialization. To optimize the use of natural resources and concrete waste, to fulfill the requirements for materials for construction, and an appropriate operation of recycling plants, there is a need for long term management plans concerning use of materials and coordination between various interests among the authorities and companies within the building and construction industry.

At the present time, the major part of the concrete waste in the world is being dumped. The future use of recycled materials in construction is, however, expected to enhance due to the following reasons:

- A general development in the public opinion regarding environmental issues leading to a political pressure in the direction of minimizing the generation and transport of waste, and regulations for waste depositing that will aim at making the recycling option more competitive.

- The rapid depletion of the remaining natural aggregate resources, mainly sand and gravel, which will lead to a lack of such materials in many regions of the world, followed by the high prices, a need for public regulations and for replacements like crushed and/or recycled aggregates. Moreover, new site for production will be located further and further away from urban areas.
- The technical development of the production and use of recycled materials will lead to more cost efficient demolition methods and recycling plants, a better control of the quality, and more knowledge on application technology.

In the following paragraphs, the major constituents of a management plan for recycling concrete waste will be discussed. The objective of the plan is to assist decision makers to achieve the goals of economic efficiency and environmental protection simultaneously in the recycling of concrete waste.

5.3.1 Management Plan for Recycling Concrete Waste

The following management plan is offered for having successful recycling. This plan is based on the management instruments proposed by Gjorv, Odd and Sakai in 2000. Their management instruments have been modified in order to suit the recycling of concrete in Egypt.

1) Basis of the Plan

The basis of any plan is to recognize the demand for the end-product. The recognition of demand for recycling concrete should be considered as stage 1 in a successful management plan. If there is a demand for the recycled concrete aggregate in the Egyptian market, then this plan should be considered.

In order to determine the demand for recycled concrete aggregate, a market survey should be performed in order to attain the respond of the parties involved in the construction industry about their perspectives regarding its application and usage.

2) Inventories

The second stage in the management plan is to identify the inventory of the main impacts associated with the manufacture, use and disposal of product, from the mining of the raw materials, energy used in its production and distribution, through to its use, possible re-use or recycling, and eventual disposal. The inventories will be the actual quantities of concrete waste resulting from the construction and demolition industry in Egypt which will act as the input product for producing the demanded product.

This stage includes the analysis for the life cycle of the product. The life cycle analysis will help in identifying all the stages of the product starting from the manufacturing of concrete from natural aggregate till the processing of this concrete in order to be recycled and used as recycled aggregate.

The recognition of the effects of construction products on the dimensions of sustainable development during and after their life time has led to the concept of Life Cycle Analysis (LCA). Life Cycle Analysis is defined by the Advanced Construction and Demolition Waste Management for Florida Builders as:

"Method to holistically evaluate the consequences associated with the cradle-to-grave life cycle of a product or process".

The phrase "Cradle to Grave" has often been used to consider the use of components of a building system once the component has fulfilled its useful life. Changing the paradigm from "Cradle to Grave" to "Cradle to Reincarnation" emphasizes the recovery of the material. The reincarnation of the material implies the reuse and/or recycling in order to retrieve waste material from de-manufacture course to manufacture process. Figure 5.1 depicts the life cycle of the material from "Cradle to Reincarnation" point of view.

Most LCAs are simply inventories of energy and material consumption and released to the environment: emissions to air and discharges to water and the level of solid waste generated. Carrying out an LCA is a relatively straight forward exercise, providing the boundary of the study has been clearly defined, the methodology is applied, and the data is accessible (Rainbow, 1994).

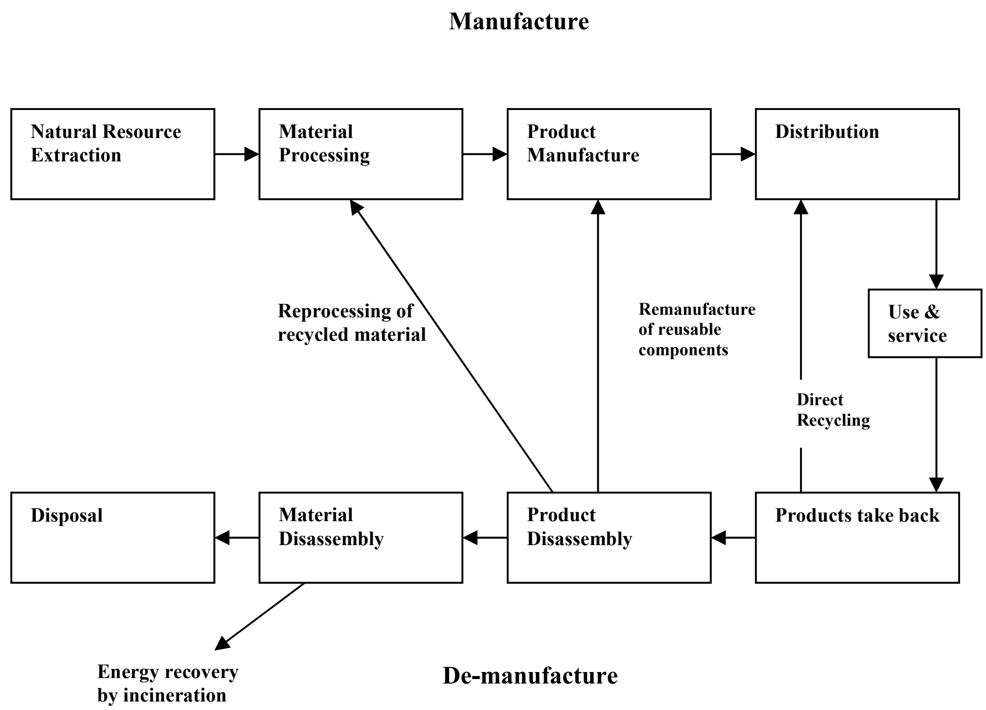


FIGURE 5.1: LIFE CYCLE ANALYSIS - CRADLE TO REINCARNATION
(Advanced C&D Waste Management for Florida Builders, 1998)

In theory, decision-making ought to be straightforward. With LCAs to provide relative environmental impact, one should be able to make choices as a producer, a customer, a waste disposal authority or a civil servant. One could even dream of rationalizing decisions in terms of economic costs and environmental benefits, as illustrated in figure 5.2.

Thus, through the influence of diminishing returns and economies of scale one could achieve optimal levels of reduction, reuse, recycling, energy recovery, and final disposal. Each optimal level will represent the level of environmental protection where any amount spent or withheld would result in a reduced marginal environmental benefit.

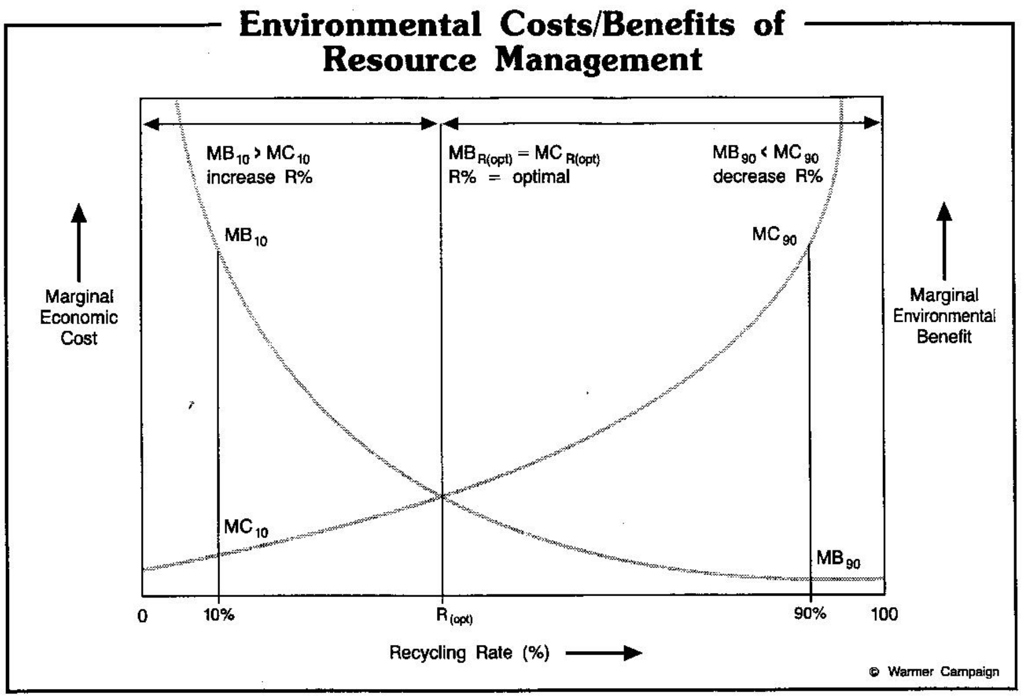


FIGURE 5.2: ENVIRONMENTAL COST/BENEFITS OF RESOURCE MANAGEMENT, (RAINBOW, 1994)

3) Research and Development

This stage involves the determination of the quantities of construction and demolition concrete waste available in the market. It also involves the accumulation of knowledge concerning the available stocks of natural aggregate which is the main competitor of the recycled aggregate. The stage also identifies the environmental aspects involved in the recycling process such as the availability of environmental laws, the location of the recycling plant, the operation noise and dust expected from the recycling plant which represent the major environmental concerns in recycling.

4) Demonstration Projects

This stage involves the gathering of the know-how of recycling in terms of plant's layout and production process and crushing mechanisms to be applied. Moreover, it includes the identification of the specifications of the end-product according to the governing codes of practices in the market. The best way to get the know-how is to visit similar projects and investigate the full details of the production process and layout of plants. Moreover, it includes the feasibility studies needed, the marketing plans and the preliminary designs for the plant.

5) Implementation

This is the final stage where the management of resources is performed. The full design of the plant, the construction of the plant, the hiring of the employees and the establishment of the quality manuals and acceptance criteria for in-coming debris are included in this stage.

Figure 5.3 summarizes the management plan for recycling concrete.

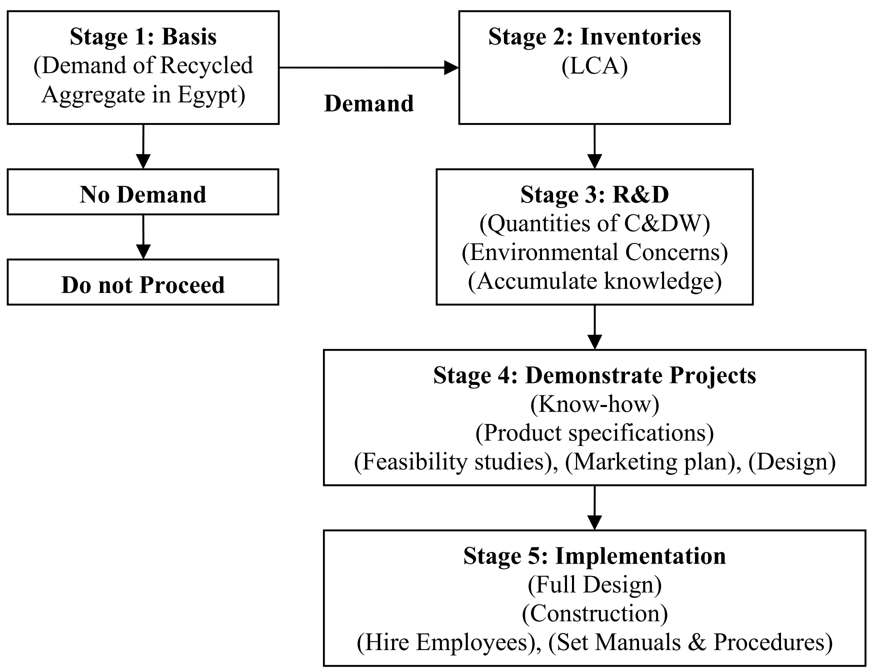


FIGURE 5.3: PROPOSED MANAGEMENT PLAN FOR RECYCLING CONCRETE

5.4 Conclusions

As a conclusion regarding the environmental, economic and management concerns in recycling concrete, one can deduce the following:

- In the selection of the recycling plant location, environmental conditions of the vicinity and legal requirements must be carefully studied and necessary countermeasures taken.
- A Key factor for the success and profitability of recycling is the location of the recycling plant.
- Recycling plants should have a minimum capacity of 110-275 metric tons per hour in order to meet the economies of scale.
- The major costs elements include: capital investment, machinery and equipment, operation costs, land, extra treatment costs of the incoming debris, transportation costs of debris to the recycling plant, transportation costs of the plant in case of mobile plants, end-product quality enhancement costs, and finally the transportation costs of the end-product to the construction site.
- A management plan was proposed for the recycling of concrete industry in Egypt. The plan has shown that the demand for the recycled aggregate in the market is the governing factor in implementing the plan.

CHAPTER 6
ECONOMIC MODEL AND PROVISIONAL GUIDELINES FOR MATERIAL QUALITY

This chapter presents both a proposed economic model for evaluating the national savings of concrete recycling in Egypt and assessing the viability of creating markets for recycled aggregates as well as provisional guidelines for material quality for the producers and users of recycled concrete aggregate in Egypt.

The developed economic model is a combination and modification of two different models generated by Xavier Duran, Helena Lenihan, and Bernadette O'Regen (University of Limerick, Ireland) in 2006, and the simulation model presented by Mala Chandrakanthi, Janaka Ruwanpura, Patrick Hettiaratchi and Bolivar Prado (University of Calgary, Canada) in 2002. The first model assesses the economies of creating markets for recycled construction and demolition (C&D) waste in the Republic of Ireland. The model was based on the potential decisions facing the waste producer and the aggregate user. This model recommends that economic viability is likely to occur when the cost of land filling exceeds the cost of brining the waste to the recycling center and the cost of using primary aggregates exceeds the cost of using recycled aggregates (Duran, Lenihan & O'Regen, 2006). The second model predicts waste generation rates as well as determining the economic advantages of recycling at construction sites (Chandrakanthi, Ruwanpura, Hettiaratchi & Prado, 2002).

The provisional guidelines proposed develop standards to guarantee the quality of recycled aggregates. These guidelines set out the control process for producers so that they can ensure their product to be fully recovered and also provide the users with the specification limits for some properties of the recycled aggregate in order to be the base for establishing a code of practice for recycled aggregate in Egypt.

6.1 The Economic Model

6.1.1 Assumptions Underlying the Model

- Waste producers and aggregate users' decisions are assumed to be based on cost minimization opportunities. This is a reasonable assumption to make since most private contractors usually operate under conditions of cost minimization or profit maximization.
- The Construction and Demolition (C&D) waste producer can either dispose at the landfill site or in the potential recycling center.
- Aggregate users can only use quarried stone or recycled C&D waste concrete.
- No illegal dumping is allowed.
- Recycling centers are competitive. This implies that the objective of the recycling center is not to make a profit and thus the prices charged for C&DW going into the center and for recycled aggregates need only to cover the cost of recycling. This assumption is realistic if the government of Egypt manages the recycling center. Another section in this chapter analyses the situation whereby recycling centers make a profit.

6.1.2 Decision of where to dispose of the Construction and Demolition Waste

The decision of the building or demolition contractor must be analyzed. Contractors will bring the waste to a recycling center as long as this cost is lower than that of bringing it to the landfill site. In calculating the costs, the contractor will make a good consideration for the transport costs as well as the other costs generated from bringing the waste to the recycling center. Equation 6.1 (Duran, Lenihan & O'Regen, 2006) summarizes the decision of the contractor to bring the C&D waste to the recycling center instead of the landfill site:

$$\mathbf{T1 + C1 > Tr + Cr + Er} \qquad \textit{(Equation 6.1)}$$

Where: T1 = cost per metric ton of transporting unsorted waste to landfill site; C1 = cost per metric ton of disposing of unsorted waste in landfill; Tr = cost per metric ton of transporting waste to recycling center; Cr = cost per metric ton of bringing waste to recycling center; and Er = extra costs per metric ton incurred by waste producer of bringing waste to recycling center (i.e. cost of waste separation).

The left hand side of the equation summarizes the cost of land filling the C&D waste, while the right hand side summarizes the cost incurred by the generator of waste disposing of the waste at one potential recycling center. The term Er is mainly explained by the fact that most of the potential recycling centers will only accept C&D waste under the condition that it is not mixed. This implies that the contractor will incur the cost of separation. If the recycling center accepts mixed waste, Cr is likely to be higher as the separation will have to take place in the center. Therefore, construction and demolition contractors will have to make the decision of either separating the waste themselves and incur Er or letting the recycling center do the separation itself and incur higher Cr.

6.1.3 Decision of which aggregate to use

The second condition to ensure the creation of markets for recycled C&D waste requires the aggregate user to opt for recycled aggregates. The user will use recycled aggregates only if they are cheaper and of similar quality to primary aggregates. The user will also consider the transportation costs and the additional costs from using the material. The decision of the aggregate user to use recycled aggregates is summarized in equation 6.2 (Duran, Lenihan & O'Regen, 2006).

Qp + Tq > Eru + RCp + Tru ***(Equation 6.2)***

Where: Qp = the price per metric ton of newly quarried product at quarry gate; Tq = the cost per metric ton of transport from quarry to site; Eru = any extra costs (such as costs that might be required for enhancing the quality in the form of extra cement) per metric ton created by using the recycled product; RCp = price per metric ton of recycled product at the recycling center gate; and Tru = the cost per metric ton of transport from recycling center to site.

The left hand side of the equation summarizes the cost incurred by the aggregate user when primary aggregates are brought and the right hand side summarizes the cost incurred when recycled aggregates are purchased. Eru is not relevant if recycled aggregates have the same characteristics as primary aggregates.

The cost of recycling relates equations (6.1) and (6.2) as it determines the values of Cr and RCp. The cost of recycling is composed of capital costs (crushers, screeners, and other machinery used in the recycling process), labor costs, the site cost and operating costs (energy, water, administration). The total cost of production must be divided by the units produced to find the unit cost. This must be covered by the waste producer (Cr) and the aggregate user (RCp). This is summarized in equation 6.3 (Duran, Lenihan & O'Regen, 2006):

$$\textbf{Recycling Costs} \leq \textbf{Cr} + \textbf{RCp} \qquad \textit{(Equation 6.3)}$$

6.1.4 The Imposition of Taxes

The imposition of taxes on land filling and the use of primary aggregates result in an increase in the cost of the use of landfill and primary aggregates. The imposition of taxes on land filling increases the cost of land filling per metric ton before the tax ($C1^b$) by amount (T^1) thus resulting in a higher cost per metric ton of land filling after tax ($C1^t$) as specified in equation 6.4 (Duran, Lenihan & O'Regen, 2006):

$$\mathbf{C1^t = C1^b + T^1} \qquad \textit{(Equation 6.4)}$$

The imposition of a tax on the use of primary aggregates increases the cost of using primary aggregates. Thus, such a tax will increase the cost per metric ton of primary aggregates before the tax (Qp^b) by amount (T^q) resulting in a higher cost per metric ton of land filling after tax (Qp^t) as expressed below in equation 6.5 (Duran, Lenihan & O'Regen, 2006):

$$Qp^t = Qp^b + T^q \qquad \textit{(Equation 6.5)}$$

Equations (6.1) and (6.2) can be substituted by equations 6.6 and 6.7 (Duran, Lenihan & O'Regen, 2006) to include taxes as follows:

$$T1 + C1^t > Tr + Cr + Er \qquad \textit{(Equation 6.6)}$$

$$Qp^t + Tq > Eru + RCp + Tru \qquad \textit{(Equation 6.7)}$$

Thus, equation (6.6) summarizes the decision of a C&D waste producer to bring waste to the recycling center. The C&D waste producer will bring this waste to the recycling center as long as the cost of disposal at landfill (including the imposition of a tax) is higher. In turn, equation (6.7) summarizes the decision of the aggregate user to use recycled aggregates as their cost is lower than using primary aggregates when including the imposition of a tax per metric ton of primary aggregates.

6.1.5 Use of Subsidies

The use of taxes has been seen as a tool to encourage recycling through the increase in the cost of either land filling or using primary aggregates but still policy makers can also encourage recycling through the use of subsidies. Thus, policy makers could offer subsidies to those using recycled aggregates and those disposing of waste in recycling centers to result in a decrease in the cost incurred by users of recycled aggregates and producers of C&D waste bringing their C&D waste to the recycling centers.

The adoption of a subsidy on the use of a recycling center reduces the cost of bringing one metric ton of C&D waste to the recycling center (Cr^b) by (S^r) thus resulting in a lower cost of bringing one metric ton of C&D waste to the recycling center (Cr^s) as specified in equation 6.8 (Duran, Lenihan & O'Regen, 2006):

$$\mathbf{Cr^s = Cr^b - S^r} \qquad \textit{(Equation 6.8)}$$

In turn, the use of subsidies on the use of recycled aggregate reduces the cost of one metric ton of recycled aggregate (RCp^b) by (S^e) thus resulting in a lower cost of using one metric ton of recycled product (RCp^s) as in equation 6.9 (Duran, Lenihan & O'Regen, 2006):

$$\mathbf{RCp^s = RCp^b - S^e} \qquad \textit{(Equation 6.9)}$$

Equations (6.1) and (6.2) can then be substituted by equations 6.10 and 6.11 (Duran, Lenihan & O'Regen, 2006) to include the use of subsidies as follows:

$$\mathbf{T1 + C1 > Tr + Cr^s + Er} \qquad \textit{(Equation 6.10)}$$

$$\mathbf{Qp + Tq > Eru + RCp^s + Tru} \qquad \textit{(Equation 6.11)}$$

Thus, equation (6.10) summarized the decision of a C&D waste producer to bring waste to the recycling center as the cost of disposing C&D waste in the landfill site is higher than the cost of bringing it to the potential recycling center when a subsidy is available. In turn, equation (6.11) summarizes the decision of an aggregate user to use recycled aggregates as their cost when including a subsidy is lower than using primary aggregates. Appendix E estimates the quantity of construction concrete waste in the Egyptian construction industry.

6.1.6 Application of the model to the case of Cairo/Egypt

The following scenarios build on the proposed economic model and use data attained from the Egyptian market to assess the economic viability of creating markets for the recycled C&D waste. Two scenarios have been developed. The first one assumes a stationary recycling plant and the second one assumes a mobile recycling plant.

Scenario 1: Stationary Recycling Plant in New Cairo city, Greater Cairo

1) Location: it is assumed that the recycling plant is located in New Cairo city in Greater Cairo. The reasons behind this assumed location are as follows:

- To be close to a ready-mix concrete batch plant already located in this zone.
- To be close to the heavy industrial zones (such as 10th of Ramadan city) and the other residential zones (New MADINATY, etc).
- To be close to the massive construction activities undergoing in the zone and its surroundings.
- To be near to the landfill/dumping sites existing in the zone.
- To be near to the quarries of virgin coarse aggregate serving the zone.

The above-mentioned reasons would permit the suppression of variables T1, Tr, Tq and Tru in the proposed economic model.

2) Output: This recycling center/plant is assumed to be capable of recycling 360,000 metric tons per year over 5 years (250 metric tons per hour x 6 hours per day x 20 days per month x 12 months).

3) Machinery: Information supplied by the market (DECOM Ready-mix concrete) suggested that such a recycling center would use one crusher (700,000 $), one screener (300,000 $) and one wheeled loader (175,000 $) using 151 diesel /hour plus other miscellaneous costs estimated at 50,000 $. It is assumed that the machinery is bought and paid in full and there is no scrap value. The maintenance cost for the crusher is estimated at 12,000 $ per year (price in 2007), i.e. approximately 68,000 EGP (exchange rate: 1 $ = 5.68) and for the screeners and the wheeled loaders, it is estimated at 6,000 $ per year, i.e. approximately 34,000 EGP.

4) Labor Manpower: There are two qualified workers required at approximately (3,000 EGP per month each), i.e. 6,000 EGP per month total. Also two unqualified workers are needed at (1,000 EGP per month each), i.e. 2,000 EGP per month total. A manager for the plant is estimated at 12,000 EGP per month.

5) Other: Operating costs are assumed to increase by 3% per year.

Scenario 2: Mobile Recycling Plant serving various areas in Egypt

1) Output: This mobile recycling center is assumed to service 15 urban areas in Egypt to recycle a total quantity of 720,000 metric tons per year (8 hours/day, 15 days per month) for 5 years, i.e., 500 metric tons per hour capacity.

2) Transport: The recycling center is transported 15 times per year between the smaller urban centers at a cost of 10,000 EGP.

3) Machinery: Information supplied by the market (DECOM Ready-mix concrete) suggested that such a recycling center would use one crusher (700,000 $), one screener (300,000 $) and one wheeled loader (175,000 $) using 151 diesel/hour. No other miscellaneous costs were estimated. It is assumed that the machinery is bought and paid in full and there is no scrap value. The maintenance cost for the crusher is estimated at 12,000 $ per year (price in 2007), i.e. approximately 68,000 EGP (exchange rate: 1 $ = 5.68) and for the screeners and the wheeled loaders, it is estimated at 6,000 $ per year, i.e. approximately 34,000 EGP.

4) Labor Manpower: The same assumptions as in scenario 1.

5) Other: Operating costs are assumed to increase by 3% per year.

Table 6.1: Recycling Costs in Potential Permanent & Mobile Recycling Centers in Egypt

Concept	Stationary Recycling Plant			Mobile Recycling Plant		
	Units	Unit Cost (EGP)	Total Cost (EGP)	Units	Unit Cost (EGP)	Total Cost (EGP)
Capital Costs						
Crushers	1	3,976,000	3,976,000	1	3,976,000	3,976,000
Screeners	1	1,704,000	1,704,000	1	1,704,000	1,704,000
Loaders	1	994,000	994,000	1	994,000	994,000
Other	1	284,000	284,000	---	---	---
Sub-total			**6,958,000**			**6,674,000**
Operating Costs						
Qualified Workers	2	36,000	72,000	2	36,000	72,000
Unqualified Workers	2	12,000	24,000	2	12,000	24,000
Plant Manager	1	144,000	144,000	1	144,000	144,000
Energy [l/h]	15	1,080	16,200	15	1,080	16,200
Electricity [kw]	25	576	14,400	25	576	14,400
Water [m^3]	90,000	0.35	31,500	180,000	0.35	63,000
Maintenance	1	102,000	102,000	1	102,000	102,000
End Product Quality Enhancement [MT]	360,000	7.50	2,700,000	720,000	7.50	5,400,000
Sub-total operating costs for year 1			3,104,100	---	---	5,985,600
Sub-total operating costs for year 2			3,197,223	---	---	6,165,168
Sub-total operating costs for year 3			3,293,140	---	---	6,350,123
Sub-total operating costs for year 4			3,391,934	---	---	6,540,627
Sub-total operating costs for year 5			3,493,692	---	---	6,736,846
Total 5-years Operating Costs =			13,375,988	---	---	25,792,763
Total Costs =			**20,333,988**	---	---	**32,466,763**
Cost per metric ton RCA =			**56.48**	---	---	**45.09**

<u>Assumptions used in Table 6.1</u>:

1) Qualified workers: EGP 3,000 per month each x 12 months.

2) Unqualified workers: EGP 1,000 per month each x 12 months.

3) Plant manager: EGP 12,000 per month x 12 months.

4) Energy (Stationary): EGP 0.75 per solar liter x 6 hours x 20 days x 12 months.

5) Energy (Mobile): EGP 0.75 per solar liter x 8 hours x 15 days x 12 months.

6) Electricity (Stationary): EGP 0.40 per kw x 6 hours x 20 days x 12 months.

8) Electricity (Mobile): EGP 0.40 per kw x 8 hours x 15 days x 12 months.

9) Water: an assumption was made such that each 1 cubic meter RCA requires 0.5 cubic meter of water for washing and treatment at a cost of EGP 0.35 per cubic meter of water. Also the density of RCA was used as 2,000 kg/m^3.

10) End product quality enhancement: assumption was made such that one half of a cement bag will be required to enhance the quality of the end-product. The current cement price is approximately 300 EGP per metric ton. Thus, one half of a cement bag will cost 7.50 EGP

11) Operating costs were assumed to increase by 3% per year.

12) Value of land was not considered.

13) The unit values for electricity, energy (solar fuel) and water are the average unit values prevailing in the Egyptian market in year 2007.

<u>Estimation of Savings Resulting for the Above-mentioned Scenarios</u>

The savings encountered from the above-mentioned scenarios are as follows. Table 6.1 shows the recycling costs incurred in the potential permanent and mobile recycling plants. These costs were attained from the Egyptian market in 2007 from various sources as clarified in the remarks following table 6.1. The objective of the proposed scenarios is to calculate the savings that could be achieved for the national economy as a result of recycling the construction concrete waste.

The savings resulting from the mentioned scenarios are estimated by using the equation:

Savings = [(C1 – Cr) + 0.99(Qp – RCp)] x Quantity Produced ***(Equation 6.12)***

Equation 6.12 (Chandrakanthi, Ruwanpura & Hettiaratchi, 2002) calculates the savings encountered. These savings are an estimation of the efficiency gains resulting from the use of the recycling center to dispose of the C&DW and the use of secondary aggregates. It is assumed that only 99% of the incoming waste is recycled. Er is not considered.

The equation was derived from the main model equations (6.1 & 6.2) as follows:

T1 = Tr (assumption was made such that the recycling plant and the land-fill are located close to each other).

Er = 0 (assumption was made such that there are no costs incurred for separation of wastes as the plant will do it for free).

Thus, savings from disposing of waste in the recycling plant = C1 – Cr

Also, Tq = Tru (assumption was made such that the recycling plant and the land-fill are located close to each other).

Eru = (cost of end-product quality enhancement as shown in the operating costs in table 6.1).

Thus, savings from using recycled aggregate instead of natural aggregate = Qp – RCp

C1: cost per metric ton of disposing of unsorted waste in landfill, is calculated as follows:

C1 was reported by the Egyptian government to be 100 EGP per metric ton (Private Communication with Dr. Salah El-Haggar).

Cr: cost per metric ton of bringing waste to recycling center, is calculated as follows:

In order to encourage waste to be brought to the center, Cr is assumed to be zero as the waste is assumed to be accepted free of charge.

Qp: the price per metric ton of newly quarried product at the quarry gate is calculated as follows:

The average selling price of primary coarse aggregate on cost and freight basis to New Cairo city is approximately 36.00 EGP per metric cube. This price is attained from ATAQA Suez quarries. The price includes about 40% of it as transportation costs from the quarry to a distance of approximately 140 km, i.e. 36 EGP/m^3 x 40% = 14.40 EGP/m^3. Therefore, deducting the cost of transportation would lead to a selling price at the quarry gate of 21.60 EGP/m^3. This price is Qp in cubic meters.

Therefore, in order to calculate Qp in metric tons, an assumption was made such that the primary coarse aggregate has an approximate dry density of 1600 kg/m^3, i.e. 1.6 tons/m^3. Thus, Qp in tons could be calculated as: Qp in $m^3 \div 1.6 = 13.50$ EGP/ton.

RCp: price per metric of recycled product at the recycling center gate, is calculated as follows:

RCp is used as 13.50 EGP (i.e. equal to Qp) for 1 metric ton as the manager, hired by the government, of the recycling center must ensure that the cost of the primary aggregate is not cheaper than that of recycled aggregate; i.e. RCp + Cr $\geq$ 13.50 EGP.

Therefore, the savings are calculated as follows in table 6.2:

Table 6.2: Savings Encountered in Permanent and Mobile Recycling Centers

	Permanent Plant	Mobile Plant
Quantity of end recycled product (MT)	360,000	720,000
Total cost in EGP	20,333,988	32,466,763
Cost per metric ton in EGP	56.48	45.09
C1 in EGP	100.00	100.00
Cr in EGP	---	---
Qp in EGP	13.50	13.50
RCp in EGP	13.50	13.50
Savings in EGP	**36,000,000**	**72,000,000**

It should be considered however, that the real impact of the estimated savings depends on the underlying assumptions of the model.

Economy of Scale

The study of the recycling center costs as related to the scale of the recycling center reveals that recycling would benefit from economies of scale. The more the recycling center processes, the less the long run recycling cost per metric ton.

The conclusion that economies of scale appear in recycling centers suggest that recyclers (investors) should increase the scale of the center to the point of maximum production of C&DW or the minimum demand for the recycled material.

Imposition of environmental taxes and its effect on recycling centers

The imposition of taxes/levies in the form of environmental taxes on C&DW in Egypt makes the creation of markets for the recycled C&DW more viable as it increases the cost of land-filling and the cost of the use of primary aggregates. In turn, this will result in an increase in the savings. The savings equation used before could be re-written as follows:

$$\textbf{Savings} = [(C1^t - Cr) + 0.99(Qp^t - RCp)] \times \textbf{Quantity Produced} \quad \textit{(Equation 6.13)}$$

Where: $C1^t$ = cost per metric ton of bringing unsorted waste to land-fill after the imposition of a levy (t); Qp^t = selling price per metric ton of primary aggregate at the quarry gate after the imposition of a levy (t).

This form of the equation takes into account the tax to be imposed. Assuming a levy amounting to 10% per metric ton to be imposed by the Egyptian government on the use of primary aggregates, this tax will be an incentive to decrease the production of C&DW as the higher costs are passed on to final customers (i.e. the new price of primary aggregate after the tax becomes 14.85 EGP/ton where a levy equal to 1.35 EGP/ton is imposed). Table 6.3 summarizes the effect on the savings of the potential levy.

Table 6.3: Savings Resulting from Recycling Centers and Imposition of Environmental Tax

	Permanent Plant	**Mobile Plant**
Quantity of end recycled product (MT)	360,000	720,000
Total cost in EGP	20,333,988	32,466,763
Cost per metric ton in EGP	56.48	45.09
C1 in EGP	100.00	100.00
Cr in EGP	---	---
Qp^t in EGP	13.50 + 1.35	13.50 + 1.35
RCp in EGP	13.50	13.50
Savings after (1.35 EGP tax) in EGP	**36,481,140**	**72,962,280**
Savings before tax in EGP	**36,000,000**	**72,000,000**
Increase in savings in EGP	**481,140**	**962,280**

It can be seen from table 6.3 that the imposition of a levy results in an increase in the savings accrued from recycling and thus encouraging recycling industry, reducing the use of land-fill and primary aggregates and the environmental externalities. This increase in the savings, due to the imposed levy, could be measured by the following equation:

Increase in savings = T^L x Quantity Produced x 0.99 ***(Equation 6.14)***

Where: T^L is the imposed levy in EGP/ton and it is assumed that only 99% of the incoming C&D waste is recycled.

<u>Use of subsidies and its effect on recycling centers</u>

The use of subsidies makes the creation of markets for recycled C&DW more economically viable as it reduces the cost of using the recycling center and the cost of use of recycled aggregate which is the end product of the recycling center. In turn, this will also result in an increase in the savings. The savings accrued from the subsidies could be summarized by equation 6.15 as follows:

Savings = [(C1 – Cr^s) + 0.99(Qp – RCp^s)] x Quantity Produced

(Equation 6.15)

Table 6.4 illustrates the effect of a proposed 2 EGP subsidy offered to users of primary aggregates. The table demonstrates the increase in savings due to the government subsidy given to each metric ton of recycled aggregate.

Table 6.4: Savings Resulting from Recycling Centers and Use of Subsidies

	Permanent Plant	**Mobile Plant**
Quantity of end recycled product (MT)	360,000	720,000
Total cost in EGP	20,333,988	32,466,763
Cost per metric ton in EGP	56.48	45.09
C1 in EGP	100.00	100.00
Cr in EGP	---	---
Qp in EGP	13.50	13.50
RCp^s in EGP	13.50 – 2.00	13.50 – 2.00
Savings after (2.00 EGP subsidy) in EGP	**36,712,800**	**73,425,600**
Savings before subsidy in EGP	**36,000,000**	**72,000,000**
Increase in savings in EGP	**712,800**	**1,425,600**

<u>Combined use of taxes and subsidies and its effect on recycling centers</u>

A combination of equations 6.13 and 6.15 would lead to the following equation:

Savings = [($C1^t$ – Cr^s) + 0.99(Qp^t – RCp^s)] x Quantity Produced

(Equation 6.16)

Where: $C1^t$ = cost per metric ton of bringing unsorted waste to land-fill after the imposition of a levy (t); Qp^t = selling price per metric ton of primary aggregate at the quarry gate after the imposition of a levy (t); Cr^s = cost of bringing waste to recycling center after subsidy (s) is given to waste producers; RCp^s = price per metric ton of recycled product at the recycling center gate after subsidy (s) is given to recyclers.

The results due to having a 10% levy (i.e. 1.35 EGP per metric as per current prevailing prices of primary aggregates in the market in 2007) per each metric ton of primary aggregate and 2 EGP subsidy for each metric ton recycled aggregate in the recycling center would lead to the results in table 6.5.

Table 6.5: Savings Resulting from Recycling Centers and Use of Subsidies and Imposition of Taxes

	Permanent Plant	**Mobile Plant**
Quantity of end recycled product (MT)	360,000	720,000
Total cost in EGP	20,333,988	32,466,763
Cost per metric ton in EGP	56.48	45.09
C1 in EGP	100.00	100.00
Cr in EGP	---	---
Qp^t in EGP	13.50 + 1.35	13.50 + 1.35
RCp^s in EGP	13.50 – 2.00	13.50 – 2.00
Savings after levy and subsidy in EGP	**37,193,940**	**74,387,880**
Savings before levy and subsidy in EGP	**36,000,000**	**72,000,000**
Increase in savings in EGP	**1,193,940**	**2,387,880**

It is clear from table 6.5 that the combination of taxes and subsidies optimizes the savings accrued and reduces land-filling and use of primary aggregates. The cost of subsidies shall be paid by the revenues resulting from taxes and thus the public sector does not incur cost. It should also be noted that the values of tax/levy and/or subsidy are just proposed values by the author. The author recommends that more investigations and studies should be performed by the government in this field in order to determine the optimum tax/levy and/or subsidies to be imposed and/or used.

Thus, considering the normal savings from table 6.2, one can note that the recycling of C&DW saves about 100 EGP per each metric ton of C&DW for the national economy.

6.1.7 Profitability in Recycling Plants

In the above presented model and its subsequent application to the case of the Egyptian market, it is assumed that the recycling center is competitive and is not making any profit. The above discussions and calculations were given to present the savings that could result for the national economy.

In practice, however, recycling centers are not likely to be perfectly competitive due to reasons such as the location of the recycling center or the quantity of aggregates produced. Both of these factors could enable the recycling center to possess some degree of market power. This market power in turn implies the possibility of making a profit by means of charging a price to producers of C&DW and to users of aggregates in excess of the cost of recycling.

Thus, in order to encourage the private sector in Egypt to adopt the application of recycling and the establishment of recycling centers, the following business plan is presented to the private sector in Egypt.

6.1.8 Business Plan for C&DW Recycling Centers

1] Product: Recycled Concrete Aggregate.

2] Market: Local market.

3] Competitive Edges: The recycling plant shall be assumed to have three competitive edges that will help in maintaining strong growth rates; thus increasing the market penetration. The first is quality. Product that does not meet high standards of quality is rejected as imperfects. The second competitive edge is flexibility. The plant shall be set up to allow for year round supply of product. The third is the price of the end product being sold compared to the equivalent products available in the market. The recycling center, therefore, needs to make use of the economies of scale and reduce its costs.

4] Objectives: The objectives for the first five years of operation shall include:

- Creating a product-based plant whose goal is to exceed customer's expectations.
- Increasing the efficiency of the plant's productivity by approximately 10% a year.
- Developing a sustainable recycling plant, surviving-off its own cash flow.

5] Key to Success: perform the management plan as in figure 5.3 of this study.

7] Profit Margin Calculation: if the profit is calculated as a markup of the addition of the prices charged to waste producers when no profits are made by the recycling plant (Cr) and to the aggregate users (RCp) which ensures that the cost of recycling is covered (**Recycling Costs = Cr + RCp**), as shown in equation 6.3, then the profit made by the recycler is a percentage over the recycling cost as specified in the following equation:

Profit = Recycling Costs x Z x Quantity Produced ***(Equation 6.17)***

Where Z: is assumed to be the percentage of profit over the recycling cost.

Therefore, the savings estimated in tables 6.2, 6.3, 6.4 and 6.5 will decreases as "Z" increases. Equation 6.18 relates the savings to "Z" as follows:

Savings = {[(C1 – Cr) + 0.99(Qp – RCp)] x Quantity Produced} – [(Cr + RCp) x Z x tons produced] ***(Equation 6.18)***

The term "Z" does tell the amount of profit that will be made by the recycler. In fact, the recycler can either increase the price charged for accepting the C&DW or for selling the recycled aggregates. "Z" can be broken down into the percentage over the price charged for C&DW in the recycling center (R) and the percentage over the price charged for recycled aggregates in the recycling center (U). Thus, equation 6.19 substitutes equation 6.1 as follows:

$T1 + C1 > Tr + Cr\,(1 + R) + Er$ ***(Equation 6.19)***

Equation 6.20 substitutes equation 6.2 as follows:

$Qp + Tq > Eru + RCp\,(1 + U) + Tru$ ***(Equation 6.20)***

Also equation 6.21 substitutes equation 6.3 as follows:

$\text{Recycling Costs} \leq Cr\,(1 + R) + RCp\,(1 + U)$ ***(Equation 6.21)***

Therefore, the savings that accrue could in turn be expressed as follows:

$\text{Savings} = [(C1 - Cr\,(1 + R)) + (Qp - RCp\,(1 + U)) \times 0.99)] \times \text{tons produced}$

(Equation 6.22)

Savings will be lower than in the case of non-profit recycling center as the prices charged for bringing the C&DW to the recycling center and for recycled aggregates are higher.

6.1.9 Conclusion

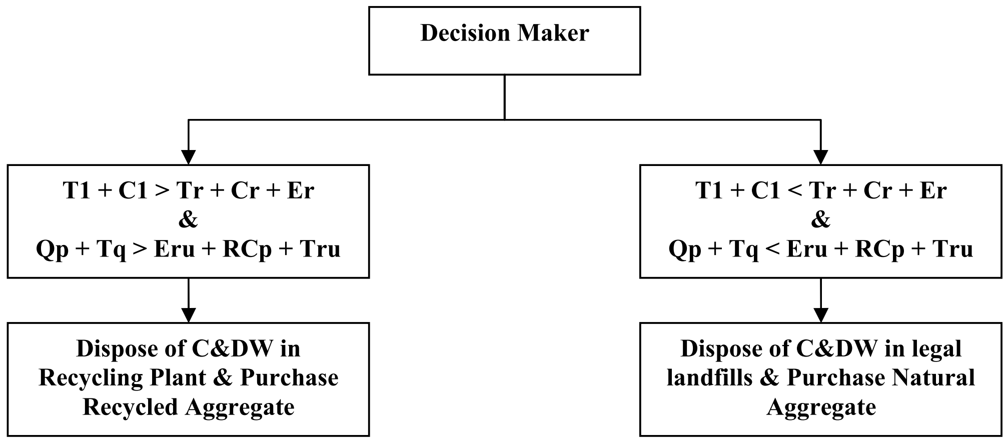
The economic model presented described the conditions that promote for an economic viable market for recycled C&DW. Viability is likely to occur when the cost of land-filling exceeds the cost of bringing the waste to the recycling center and the cost of using primary aggregates exceeds that of using recycled aggregates assuming that recycled aggregate meets quality requirements. Once these conditions are met, recycling will be economically viable and likely to occur, as it becomes a cheaper option than the use of landfill and/or primary aggregates.

Having developed a suitable framework to highlight the conditions necessary to encourage recycling of C&DW, the economic model was then applied to the case of Egypt. Two potential recycling centers were proposed. One was proposed to be located at New Cairo city and the other was proposed to be a mobile plant serving at least 15 small urban areas throughout the country. The data used in the calculations were attained from the Egyptian market in 2007. The proposed centers led to national savings. Also one important conclusion is that the recycling centers benefit from economy of scale. Thus, an increase in the scale of the center would lead to a decrease in the recycling costs. Recycling centers located close to areas with large populations and high demand for aggregates would incur lower costs per metric ton of end product and thus charge lower prices.

The model also proposed the imposition of taxes, as environmental taxes, that would increase the prices of primary aggregates and creates market for the recycled aggregates. Subsidies could also be useful if implemented by the government. The public sector shall not incur any costs as the cost of subsidies shall be paid by the revenues resulting from taxes.

Also a business plan was proposed for the private sector in Egypt in order to adopt the establishment of recycling plants. The location of the recycling center and the quantity of aggregates produced represent the major key elements for the success and profitability of the center.

Figure 6.1 summarizes the developed economic model and figure 6.2 summarizes the proposed business plan as follows:



T1 = cost per metric ton of transporting unsorted waste to landfill site; **C1** = cost per metric ton of disposing of unsorted waste in landfill; **Tr** = cost per metric ton of transporting waste to recycling center; **Cr** = cost per metric ton of bringing waste to recycling center; and **Er** = extra costs per metric ton incurred by waste producer of bringing waste to recycling center, **Qp** = the price per metric ton of newly quarried product at quarry gate; **Tq** = the cost per metric ton of transport from quarry to site; **Eru** = any extra costs (such as costs that might be required for enhancing the quality) per metric ton created by using the recycled product; **RCp** = price per metric ton of recycled product at the recycling center gate; and **Tru** = the cost per metric ton of transport from recycling center to site.

FIGURE 6.1: DEVELOPED ECONOMIC MODEL

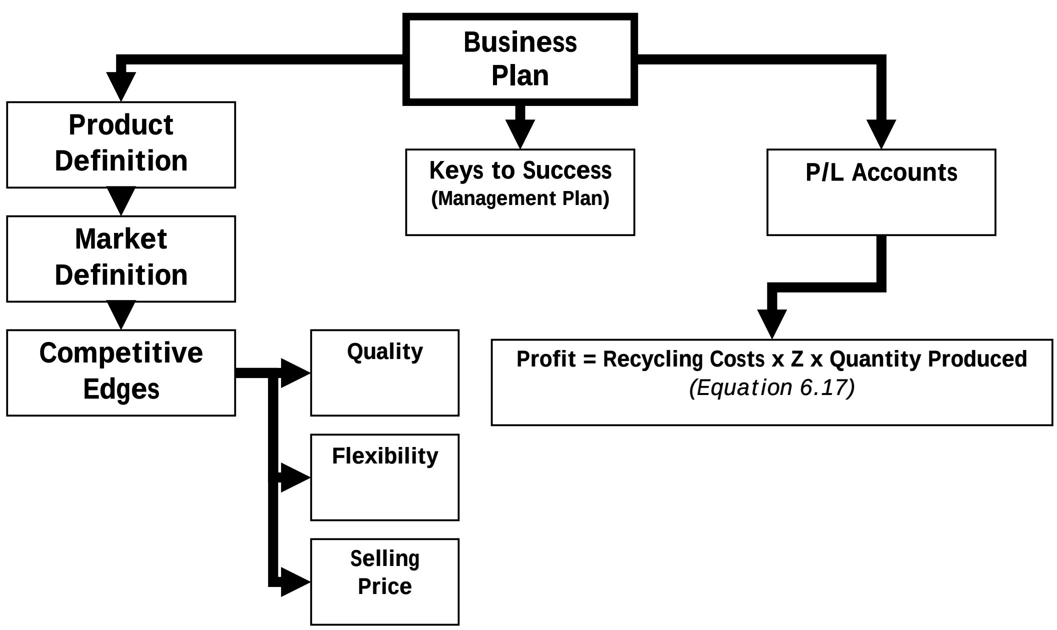


FIGURE 6.2: PROPOSED BUSINESS PLAN

6.2 Provisional Guidelines for Recycled Concrete Aggregate Quality

The provisional guidelines addressed in the following paragraphs seek to ensure that recovered aggregates meet the quality and conformity requirements for the Egyptian standards for aggregates. These provisional guidelines are based on the quality protocol produced by the "Waste and Resources Action Programme" (WRAP) in the United Kingdom (http://www.aggregain.org.uk).

6.2.1 Definitions

Aggregates recovered from processing inert wastes (Appendix D) are defined within the European and British standards and specifications as illustrated in the definitions below:

- Aggregates: Granular material used in construction. Aggregate may be natural, manufactured or recycled.
- Recycled Aggregate: Aggregate resulting from the processing of inorganic material previously used in construction.
- RA: A designation used in BS 8500 for recycled aggregate principally comprising crushed masonry (brickwork and blockwork).
- RCA: A designation used in BS 8500 for recycled aggregate principally comprising crushed concrete.
- RAP: Recycled aggregate consisting of crushed or milled asphalt. This may include millings, planings, returned loads, joint offcuts and plant waste.

6.2.2 Recycling Center Production Control

A system of the recycling center production control should be set up in accordance with the Egyptian standards for aggregates.

6.2.3 Acceptance Criteria for Incoming Waste

To ensure that only inert waste is accepted the producer should have and maintain procedures in the form of "acceptance criteria" specific to each site and/or location. The following should be included in the criteria:

a) The types of waste that are accepted.

b) The method of acceptance.

Visual inspections should be carried out on every load, on initial receipt and after tipping, to ensure compliance with the acceptance criteria. Where the percentage of any contaminant or foreign material is higher than that defined in the acceptance criteria, the consignment must be rejected. Also a record of each load delivered and accepted should be kept giving:

a) Date.

b) Nature and quality.

c) Place of origin.

d) Quantity by weighing/volume.

e) Carrier.

f) Supplier.

6.2.4 Method Statement of Production

A method statement should be prepared detailing the waste recovery process and the range of products produced. A flow chart (example Appendix B) may be used for this purpose with additional qualifications as necessary. The method statement should form a part of the recycling center control system.

6.2.5 Inspection and Testing Regime including Frequency and Methods of Test for Finished Product

The inspection and testing regime should be detailed and appropriate to the material end use, the quality of incoming waste and the complexity of the waste recovery process. Appendix C proposes the test methods that may be used as a means of either deciding or illustrating suitability for a particular end use according to the Egyptian standards and specifications.

6.2.6 Records

Records of incoming wastes and products should be kept. In addition to records, all tests carried out on samples taken shall be retained as well.

6.2.7 Proposed Specifications for Recycled Concrete Aggregate

The following are proposed specifications, limits, for some of the properties of the recycled concrete aggregate for use in the Egyptian construction industry. These limits are the results of what have been discussed in the previous chapters according to the various researches done in this field and also according to the RILEM standard specifications for recycled aggregates. Table 6.6 contains the recommended limits for some physical and mechanical properties of the recycled concrete aggregate in order to be used as a source of coarse aggregate for producing quality concrete.

The author recommends that for lower grade concrete applications, concrete with 100% recycled coarse aggregate could be allowed. Recycled fines are not recommended to be used in concrete due to the disadvantages that have been presented in chapter 4 as they increase the waste demand of fresh concrete and lower the strength and probably the durability of hardened concrete. Concrete with 100% recycled coarse aggregate can be used in benches, stools, planter walls, concrete mass walls and other minor concrete structures.

For higher grade applications, the author recommends a maximum of 20% to 30% replacement of virgin coarse aggregates by recycled aggregates and the concrete can be used for general concrete applications except in water retaining structures.

Table 6.6: Proposed Specifications for Recycled Coarse Aggregate for Concrete Production in Egypt

Properties	Proposed Limit for Recycled Concrete Coarse Aggregate	Limit in the Egyptian Code for Natural Coarse Aggregate	Test Method
Water Absorption Percentage (%)	7.00% Maximum (Refer to note 1)	2.50% Maximum (Refer to note 2)	ASTM C-127 BS 812: Part 12
Maximum content of foreign matters (metals, plastics, clay lumps, glass, asphalt, etc)	2-10 kg/m^3 As per table 4.9 in this document (Refer to note 3)	3.00% Maximum (Refer to note 4)	ASTM C-142-78 BS 882: 1992
Maximum content of Sulfates (%)	1.00% Maximum (Refer to note 5)	0.40% Maximum (Refer to note 6)	BS 812: Part 118/1988
Maximum content of Chlorides (%)	0.50% Maximum By mass of chloride ion of combined aggregate (Refer to note 5)	0.04% Maximum (Refer to note 6)	BS 812: Part 117/1988
10% fineness value (kN) [1 ton = 10 kN]	50-150 kN Minimum (Refer to note 10)	50-100 kN Minimum (Refer to note 7)	BS 812: Part 111-1990
Grading	ASTM C33/BS 812: Part 103/1985 (Refer to note 11)		
Flakiness Index (%)	40.00% Maximum (Refer to note 5)	25.00% Maximum (Refer to note 1)	BS 812: section 105.1/1989
Los Angeles Abrasion Loss (%)	40-50% Maximum (Refer to note 8)	30% Maximum (Refer to note 9)	ASTM C535-89

** For the notes, please refer to the following analysis of table 6.6.*

Analysis for Table 6.6

<u>Note (1)</u> According to the "Japanese Proposed Standard for the use of recycled aggregate" (B.C.S.J, 1977), refer to section 4.2.4 of this study.

- The proposed limit for the water absorption is attributed to the attached cement past to the particles of the recycled concrete which has higher water absorption.

<u>Note (2)</u> According to (Table 2-1) of the "Egyptian code for Designing Concrete Structures", code number 203 Revision 2 for year 2001 (refer to Appendix F).

<u>Note (3)</u> According to the "Japanese Proposed Standard for the use of recycled aggregate" (B.C.S.J, 1977), refer to table 4.9 of this study.

Type of Aggregate	**Plasters, Clay lumps & Other Impurities of Densities < 1950 kg/m^3**	**Asphalt, Plastics, Paints, Cloth, Paper, Wood & Similar Material Particles Retained on a 1.2 mm Sieve. Also Other Impurities of Densities < 1200 kg/m^3**
Recycled Coarse	Maximum 10 kg/m^3	Maximum 2 kg/m^3

<u>Note (4)</u> According to (Table 2-11-2) of the "Egyptian code for Designing Concrete Structures", code number 203 for 2003, Annex 3: Manual for laboratory testing of concrete structures (refer to Appendix F).

<u>Note (5)</u> According to "RILEM Recommendation 1994: Standard Specifications for Concrete with Recycled Aggregates" (refer to http://www.rilem.net/proceedings.php).

<u>Note (6)</u> According to (Table 2-2) of the "Egyptian code for Designing Concrete Structures", code number 203 Revision 2 for year 2001 (refer to Appendix F).

<u>Note (7)</u> According to (Table 2-18-9) of the "Egyptian code for Designing Concrete Structures", code number 203 for 2003, Annex 3: Manual for laboratory testing of concrete structures (refer to Appendix F).

<u>Note (8)</u> For the Los Angeles abrasion, recycled concrete aggregate is expected to pass these limits and cope with ASTM C-33 for LA abrasion [According to Table 4.4

(Hansen & Narud, 1983)]. For normal concrete, 50% is the limit while for concrete used for road construction purposes LA loss value not to exceed 40%.

Note (9) According to Clause (2-17-8) of the "Egyptian code for Designing Concrete Structures", code number 203 for 2003, Annex 3: Manual for laboratory testing of concrete structures (refer to Appendix F).

Note (10) BS 882 specifies that the BS 10% fines values should be more than 5 tons for normal concrete, more than 10 tons for concrete wearing surfaces, and more than 15 tons for granolithic floor finishes. The results attained in table 4.6 (Hansen, 1992) show that aggregate conforms to the BS 882 limits.

Note (11) For the grading and shape of aggregates, fine recycled aggregates are not preferred as they are usually coarser and more angular than that desired for concrete. However, this can be improved by adding finer natural blending sand in order to bring fine recycled aggregates within the grading limits of ASTM C-33. On the other hand, the coarse recycled aggregates are usually coping with ASTM C-33 and this could be seen in figure 4.6.

Concerning the other discussed properties of recycled concrete aggregate in chapter 4, one can note the following:

- For the density, the recycled aggregate's density is usually lower than the corresponding densities of virgin aggregates due to the relative low density of old mortar attached to the original aggregate particles.
- For other contaminants rather than those mentioned in table 6.6, gypsum plaster and glass should be totally avoided since 3% of gypsum plaster could lead to a 15% reduction in the compressive strength of the concrete and also the glass must be removed as it is reactive with the cement paste.

- For the compressive strength requirements, recycled aggregate concrete depends on the strength of the original concrete being recycled and also controlled by the w/c ratio of the recycled concrete. Compressive strengths of recycled coarse aggregate concrete could show acceptable results as they are lower than that of conventional concrete by not more than 1.3% to 4.5% in the case of using recycled coarse aggregate with 100% natural sand.
- For the modulus of elasticity, damping capacity, creep deformation, drying shrinkage, and tensile and flexural strengths, the results obtained for recycled aggregates show that the modulus of elasticity is lower (20% to 40%) than conventional concrete most of the time and this might be due to the mortar attached to recycled particles. For the damping capacity, results show that recycled aggregate has higher damping capacity within 16-23%. The creep deformation and the drying shrinkage are usually 50% higher than that of original concrete. The tensile and flexural strengths are almost 10% lower than for original concrete.
- For the reinforced concrete, investigations have shown that the bond strength between steel and recycled aggregate concrete is almost the same to the case of conventional concrete when using coarse recycled aggregate and 100% natural sand. However, when fine recycled aggregate is used, the bond strength is reduced by 30%.

Therefore, the author recommends further investigations and laboratory tests for the late properties of recycled aggregates in order to determine its specification limits so that it can form, in addition to the limits proposed in table 6.6, complete specification limits for the recycled aggregates for the Egyptian code.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

This chapter considers the main outcomes of the study. It presents conclusions of the conducted investigation and recommendations for future works. It also presents the general experience with recycled aggregates in concrete and also the main points characterizing the properties and quality of recycled aggregates in comparison with conventional aggregates. Moreover, it presents the economic outcomes resulting from the proposed economic model and also the outcomes of the proposed specification limits for recycled concrete aggregate.

7.1 Conclusions Regarding the Application of Recycling Construction and Demolition Waste in Egypt

In an attempt to assess the application of recycling construction and demolition waste (C&DW) for the use as a source of aggregates and its existing practices in the construction industry in Egypt, a survey on a sample of forty-four companies from selected sectors of the construction industry was conducted. From the questionnaire results, it can be concluded that:

- The application of recycling demolished concrete is limited in the Egyptian construction industry and it can be viewed as almost not applicable at all. The reasons behind this were reported to be due to the absence of codes of practice, experiences, know-how, and economic studies that could encourage starting the implementation of such an industry.
- Roads, pavements and infrastructure constructions were the three project types with the highest recommendation for the application of the concept. On the contrary, residential and administrative structures had the lowest rates.
- Construction and demolition waste management is facing some problems and barriers that hinder its successful application. These problems and barriers

could be classified into four categories of: production, processing, collecting and hauling, and land-filling.

7.2 Conclusions Regarding the Production of Recycled Concrete Aggregate

After the analysis of the outcomes of the survey and the reasons for the absence of the application of concrete recycling in Egypt, it was important to make investigations in the construction literature in order to present the know-how and experiences that have been accomplished all over the world with respect to the production of recycled concrete aggregate. The following conclusions have been met:

- Plants for production of recycled concrete aggregates are not much different from plants for production of crushed aggregate from other sources.
- There are two mechanisms of crushing. One is the closed system which has the advantage of limiting the maximum size of aggregate particle. The second is the open system which has larger capacity than the closed system but it has a disadvantage where the maximum aggregate particle size is not well defined.
- There are four types of crushers developed. The first is the jaw crusher which produces the best grain size distribution for recycled aggregate. The second is the cone crusher which is usually used as a secondary crusher as it has a maximum of 200mm feed size. The third is the swing hammer crusher which is seldom used, and the fourth is the impact crusher which is mostly used for roads construction as it is less sensitive to materials that can hardly be crushed.

7.3 Conclusions Regarding the Properties and Quality of Recycled Concrete Aggregate

Numerous laboratory experiments, field tests, and case studies have shown that it is possible to recycle concrete to produce aggregates for drainage material, shoulders, as well as new concrete pavements. These experiments and tests could be useful in proposing specifications limits for the recycled concrete aggregate, i.e., proposing a code of practice. Some main points characterizing the properties and quality of recycled aggregates, in comparison with conventional aggregates are:

- Grading and particle shape: Fine recycled aggregates are not preferred as they are coarser and more angular than that desired for the production of quality concrete. On the other hand, the coarse recycled aggregates have shown satisfactory results and they are almost similar to conventional coarse aggregates.
- Water Absorption and Permeability: High porosity due to high mortar/cement paste content.
- Density: Crushed concrete will have a bulk density somewhere in-between rock materials and light weight aggregate.
- Los Angeles Abrasion, BS Crushing value and BS 10% fineness value: recycled concrete aggregates are expected to pass the standard limits of ASTM C33 and BS 882.
- Sulfate Soundness and Chlorides: Durability aspects should be controlled. Different results were obtained from various scientists. More investigations are needed for this area.
- Contaminants: There is a risk for contamination of organic compounds, heavy metals and other environmental hazardously substances, for example from traffic and chemical industries. Glass and gypsum plaster are the most critical contaminants. Much care should be given to these two contaminants.
- Compressive Strength: Depends mainly on the strength of the original concrete being recycled and also controlled by the w/c ratio of the recycled concrete. Results have shown that coarse recycled aggregate might lead to a similar compressive strength of concrete when compared to conventional aggregate.

This is achieved when using 100% natural sand with the recycled coarse aggregate. On the other hand, fine recycled aggregates might lead to a reduction in the compressive strength within a range of 10-40%.

- Modulus of Elasticity: Lower than in the case of conventional concrete within a range of 20-40%.
- Creep deformation and Drying Shrinkage: Higher than in the case of conventional concrete.
- Tensile and Flexural Strength: Almost 10% lower than the case of conventional concrete.
- Reinforced Concrete: Bond strength between steel reinforcement and recycled aggregate concrete is almost similar to that of conventional concrete when using coarse recycled aggregate with 100% natural sand. However, when using fine recycled aggregate, bond strength might be up to 30% lower than in case of conventional concrete.
- Quality of recycled materials can be hard to control if the aggregate production is to be based on a general reception of urban building waste from a variety of sources.

7.4 Conclusions Regarding the Environmental Concerns of Concrete Recycling

The operation of a crushing and screening plant is always accompanied by the generation of noise and dust. Therefore, in the selection of plant location, environmental conditions of the vicinity and legal requirements must be carefully studied and necessary countermeasures taken. However, the early concern about noise and dust problems when crushing concrete in mobile plants in urban areas has apparently been somewhat exaggerated.

7.5 Conclusions Regarding the Economic Concerns of Concrete Recycling

- A Key factor for the success and profitability of recycling is the location of the recycling plant.
- Recycling plants should have a minimum capacity of 110-275 metric tons per hour in order to meet the economies of scale.
- The major costs elements include: capital investment, machinery and equipment, operation costs, land, extra treatment costs of the incoming debris, transportation costs of debris to the recycling plant, transportation costs of the plant in case of mobile plants, end-product quality enhancement costs, and finally the transportation costs of the end-product to the construction site.

7.6 Conclusions Regarding the Developed Economic Model

An economic model was developed in this study to assess the economic viability of creating markets for recycled concrete aggregate in Egypt. The economic model developed is presented to both the government of Egypt; in order assess the national savings that could result from recycling the construction and demolition concrete waste, and also to the private sector in Egypt in order to be guidance for a successful business start up.

It was proposed by the study that changing the prices of primary and secondary aggregates be brought about through a tax or industry levy on the production of primary aggregates or subsidies to be given to the production of secondary aggregates. This measure would command greater favor if, at the same time, ways were found to increase expenditure on environmental schemes.

The objectives of a tax or levy in addition to the proposed economic model would be most likely to be achieved in the context of a package of administrative and regulatory measures including:

1. Greater information on the availability and applications of secondary material used.
2. Planning directives identifying waste material tips that are available for re-use.
3. Support for research into high value applications, including lightweight aggregates.
4. Planning regulations to facilitate the imposition of land restoration conditions in cases where extraction and waste disposal proceed without any conditions.
5. Support for technical research into the properties of certain materials.
6. Further development of specifications for the use of recycled aggregates and in particular, demolition and construction wastes for which there is great potential for greater use.
7. Directives to local planning authorities in urban areas to identify sites for recycling plants for demolition and construction wastes.
8. Grants to overcome transportation difficulties associated with secondary materials.
9. When comparing the recycled concrete aggregates with conventional aggregates in terms of economy wise in Egypt at the present time, it might be discovered that the use of recycled concrete aggregate for general construction purposes in Egypt is more costly than the use of conventional aggregate. However, this situation is expected to change gradually in favor of recycled aggregates. For one thing, it is expected that the extra cost which is now commonly charged for the processing of old concrete and mixed demolition rubble can be lowered once the initial developing phase is over. Also the price of conventional aggregates will probably continue to rise in the future as raw materials get scarcer and transportation costs continue to rise. Moreover,

dumping charges are certain to rise steeply over the next decades as the quantities of demolition debris continue to increase and also as the environmental regulations become more complicated.

10. Recycling concrete could result in good national savings and would also lead to saving about 5.75% of the annual consumption of conventional aggregates.
11. Recycling of each metric ton of C&DW saves about 100 EGP for the national economy.
12. A business plan and a management model were proposed for the private sector in Egypt in order to adopt the establishment of recycling plants. The location of the recycling center and the quantity of aggregates produced represent the major key elements for the success and profitability of the center.

This study spells a bright future for the recycling of concrete, provided that all parties involved proceed with reasonable prudence in order to avoid set-backs which may affect in unfavorable ways on the reputation of recycled concrete aggregate.

7.7 Conclusions Regarding the Proposed Specification Limits for Recycled Concrete Aggregate

The study has proposed some specification limits for some of the properties of recycled concrete aggregate and has compared them with the Egyptian code limits for similar properties regarding the conventional aggregate. The following properties are the ones that the study has proposed specification limits for regarding the recycled concrete aggregate:

- The water absorption percentage: 7% maximum.
- The content of foreign matters: 2-10 kg/m^3 maximum.
- The content of sulfates: 1% maximum.
- The content of chlorides: 0.5% maximum by mass of chloride ion.
- The 10% fineness value: 50-150 kN minimum.

- The grading of aggregate: ASTM C33 & BS812: part 103/1985.
- The flakiness index: 40% maximum.
- The Los Angles abrasion loss percentage: 40-50% maximum.

7.8 Recommendations for Future Studies

From the previously inducted thesis research, the author recommends the following subjects for future studies:

- A more detailed study of the demolition and construction waste industry in Egypt. This industry has the potential to supply large volumes of graded aggregates.
- Assigning monetary values to environmental amenity is proposed.
- Detailed economic feasibilities for the implementation of recycling concrete as a source of aggregates are needed.
- More investigations and experiments are required for determining the optimum properties of recycled aggregate concrete.
- The Egyptian government is required to be more involved in the above-mentioned recommendations in order to determine the real national savings and benefits that could result from the adoption of recycling construction and demolition concrete wastes.
- Public awareness should be raised by educational campaigns in order to demonstrate and clarify the concept of recycling construction and demolition concrete benefits.
- Dumping of construction and demolition waste should be delegated to specialized firms in order to provide better control and avoid illegal dumping.

- An electronic monitoring system is another potential area of study. The system should be designed so that it can predict the expected concrete waste resulting from any construction project.
- More development is required to figure out a scientific methodology to quantify the construction and demolition waste.

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APPENDIX A
SURVEY QUESTIONNAIRE AND SURVEY DATA

RESEARCH SURVEY QUESTIONNAIRE

Name of Office/Firm:
Address:
Phone No.:
Person Filling-out questionnaire:
Position:

1- What is the type of service(s) offered by your office/firm?

2- Does your firm Know recycled concrete aggregate [RCA]?

If yes, check the construction activities in which RCA is used:

a- Residential buildings ( )

b- Administrative buildings ( )

c- Infrastructure ( )

d- Roads construction ( )

e- Other(s) ( )

If other(s), please specify:

3- What is the annual volume of work conducted by the office/firm?

a- From LE 50,000 to 100,000.

b- From LE 100,000 to 1,000,000.

c- From LE 1,000,000 to 10,000,000.

d- More than LE 10,000,000.

4- Do you know of any codes of practice governing the usage of RCA in Egypt?

5- What are the major sources of RCA?

6- Where are the major sources of RCA?

7- What is the annual volume of concrete works performed by your office/firm with respect to RCA?

8- What are the main problems encountered in the industry of RCA?

9- In a construction project, would the type of contract affect the usage of RCA?

a- Yes

b- No

If yes, which are the most common types of contracts that encourage the use of RCA?

a- Unit Price Contracts.

b- Lump Sum Contracts.

c- Cost plus Contracts.

d- BOOT Contracts.

e- BOT Contracts.

f- Others, specify --.

10- For what size of projects should RCA usage be recommended?

a- For projects costing more than LE 100,000.

b- For projects costing more than LE 500,000.

c- For projects costing more than 1,000,000.

d- All project sizes.

11- What are the optimal crushing mechanisms that you would recommend?

12- What are the factors that affect the decision of using RCA in a project?

13- Could you provide an actual case study where your office/firm has utilized RCA[1]:

a- Project Title: ---

b- Project Type: ---

c- Project Location: ---

d- Work Volume: --

e- Contract Type: ---

[1] Supporting the case study with documents would be appreciated.

f- For which activities in the project RCA was used: ---

----

g- What was the volume in cubic meter of RCA used in the project: ------------------------------

h- Source(s) of RCA: ---
----

i- Crushing mechanism used: --

----

j- The result of the study (to be filled by the evaluator): --
----

Table A.1: List of Companies Surveyed

Company Name	CD[b]	PM[c]	RM[d]	C[e]	DC[f]	OWNER[g]	LA[h]
Alkan Construction				*			
Ericson				*			
Washington Construction				*			
Conserve				*			
Aresco				*			
Arkedia						*	
Asec	*	*				*	
Bin Laden				*			
EGYDAN		*					
El Khorafy Group				*		*	
FLShmidth	*	*					
Osman Group SCIC				*			
Sabbour Associates	*	*					
Ginza				*			
DAMAC						*	
Al-Amar		*					
CONTRATECH		*					
Petrojet				*			
Look Pavilion	*	*					
AWA	*						
ORASCOM OCI				*			
H. Allam Sons				*			
CEMEX			*				
Misr Cement Co			*				
Ready Mix			*				
Misr Consulting Engineers	*						
MACO				*			
Private Contractors					16		
G. Cairo Districts Authorities							*
Total Participating Firms	6	7	3	13	16	4	1
Total Firms Aware RCA	6	5	3	10	3	2	0
Percentage of Firms Aware of RCA	100%	71%	100%	77%	19%	50%	0%
Total Firms Adopting RCA	0	0	0	1	0	0	0
Percentage of Firms Adopting RCA	0%	0%	0%	8%	0%	0%	0%

[b] Consultant/Designer
[c] Project Management
[d] Ready-mix concrete plants
[e] Construction Firm
[f] Demolition Contractor
[g] Investor
[h] Local Authorities

Table A.2: Volume of Work of Companies Surveyed

Company Name	CD	PM	RM	C	DC	OWNER	LA
Alkan Construction				L			
Ericson				L			
Washington Construction				L			
Conserve				M			
Aresco				L			
Arkedia						L	
Asec	L	L				L	
Bin Laden				L			
EGYDAN		L					
El Khorafy Group				L		L	
FLSmidth	L	L					
Osman Group SCIC				L			
Sabbour Associates	L	L					
Ginza				L			
DAMAC						L	
Al-Amar		M					
CONTRATECH		S					
Petrojet				L			
Look Pavilion	M	M					
AWA	L						
ORASCOM OCI				L			
H. Allam Sons				L			
CEMEX			L				
Misr Cement Co			L				
Ready Mix			L				
Misr Consulting Engineers	L						
MACO				S			
Private Contractors					16 P		
G. Cairo Districts Authorities							N/A
Total Participating Firms	6	7	3	13	16	4	1
Total (L)	5	4	3	11	---	4	N/A
Percentage of (L) to total	83%	57%	100%	84%	0%	100%	N/A
Total (M)	1	2	---	1	----	---	N/A
Percentage of (M) to total	17%	29%	0%	8%	0%	0%	N/A
Total (S)	---	1	---	1	16	---	N/A
Percentage of (S) to total	0%	14%	0%	8%	100%	0%	N/A

* L: Large Scale company (volume: minimum 10M EGP yearly).
* M: Medium Scale company (volume: minimum 1M EGP yearly).
* S: Small Scale company (volume: 100K EGP yearly).
* P: Private contractors and demolition contractors (volume: minimum 50K EGP yearly).
* N/A: Not Applicable.

Table A.3: Annual Concrete Volume of Work of Companies Surveyed

Company Name	CD	PM	RM	C	DC	OWNER	LA
Alkan Construction	---	---	---	6	---	---	---
Ericson	---	---	---	0.5	---	---	---
Washington Construction	---	---	---	0.6	---	---	---
Conserve	---	---	---	0.5	---	---	---
Aresco	---	---	---	5	---	---	---
Arkedia	---	---	---	---	---	---	---
Asec	---	---	---	---	---	---	---
Bin Laden	---	---	---	6	---	---	---
EGYDAN	---	---	---	---	---	---	---
El Khorafy Group	---	---	---	1	---	---	---
FLSmidth	---	---	---	---	---	---	---
Osman Group SCIC	---	---	---	1	---	---	---
Sabbour Associates	---	---	---	---	---	---	---
Ginza	---	---	---	8	---	---	---
DAMAC	---	---	---	---	---	---	---
Al-Amar	---	---	---	---	---	---	---
CONTRATECH	---	---	---	---	---	---	---
Petrojet	---	---	---	10	---	---	---
Look Pavilion	---	---	---	---	---	---	---
AWA	---	---	---	---	---	---	---
ORASCOM OCI	---	---	---	15	---	---	---
H. Allam Sons	---	---	---	12	---	---	---
CEMEX	---	---	350	---	---	---	---
Misr Cement Co	---	---	270	---	---	---	---
Ready Mix	---	---	190	---	---	---	---
Misr Consulting Engineers	---	---	---	---	---	---	---
MACO	---	---	---	0.5	---	---	---
Private Contractors	---	---	---	---	0.5x16	---	---
G. Cairo Districts Authorities	---	---	---	---		---	---
Total	---	---	810	66.1	8	---	---

- Values of concrete volume are in 1,000 cubic meters per year.
- Values were provided by construction firms, ready-mix plants and demolition contractors only.

Table A.4: Problems facing Recycling as reported by Survey Participants

Company Name	LOE	LOK	AOC	EEC	AME
Alkan Construction	*	*	*	*	*
Ericson			*		
Washington Construction			*		
Conserve	*	*	*	*	*
Aresco			*		
Arkedia	*	*	*	*	*
Asec			*		
Bin Laden	*	*	*	*	*
EGYDAN	*	*	*	*	*
El Khorafy Group	*	*	*	*	*
FLSmidth			*		
Osman Group SCIC	*	*	*	*	*
Sabbour Associates	*	*	*	*	*
Ginza	*	*	*	*	*
DAMAC	*	*	*	*	*
Al-Amar	*	*	*	*	*
CONTRATECH	*	*	*	*	*
Petrojet	*	*	*	*	*
Look Pavilion	*	*	*	*	*
AWA			*		
ORASCOM OCI			*		
H. Allam Sons			*		
CEMEX			*		
Misr Cement Co			*		
Ready Mix			*		
Misr Consulting Engineers			*		
MACO	*	*	*	*	*
Private Contractors	**16 ***	**16 ***	**16 ***	**---**	**16 ***
G. Cairo Districts Authorities	*	*	*	*	
Total	**32**	**32**	**44**	**32**	**31**
Percentage out of total 44 firms	**64%**	**64%**	**100%**	**64%**	**62%**

- LOE: Lack of Experiences.
- LOK: Lack of Know-how.
- AOC: Absence of Codes of practices.
- EEC: Environmental and Economic Concerns.
- AME: Absence of Management and Economic models.

Table A.5: Effect of Contract Type on Recycled Concrete Aggregate

Company Name	UP	LS	CP	BOOT	BOT
Alkan Construction	*				
Ericson	*				
Washington Construction	*				
Conserve	*				
Aresco	*				
Arkedia	NE	NE	NE	NE	NE
Asec	*				
Bin Laden	*				
EGYDAN	NE	NE	NE	NE	NE
El Khorafy Group	*				
FLSmidth	NE	NE	NE	NE	NE
Osman Group SCIC	*				
Sabbour Associates	NE	NE	NE	NE	NE
Ginza	*				
DAMAC	*				
Al-Amar	*				
CONTRATECH	*				
Petrojet	*				
Look Pavilion	NE	NE	NE	NE	NE
AWA	NE	NE	NE	NE	NE
ORASCOM OCI	*				
H. Allam Sons	*				
CEMEX	*				
Misr Cement Co	*				
Ready Mix	*				
Misr Consulting Engineers	NE	NE	NE	NE	NE
MACO	*				
Private Contractors	16 *				
G. Cairo Districts Authorities	*				
Total	37				
Percentage out of total 44 firms	84%				

* UP: Unit Price Contracts.
* LS: Lump Sum Contracts.
* CP: Cost plus Contracts.
* BOOT: BOOT Contracts.
* BOT: BOT Contracts.
* NE: No Effect.

APPENDIX B
EXAMPLE OF A FLOW CHART FOR ACCEPTANCE AND PROCESSING OF WASTE

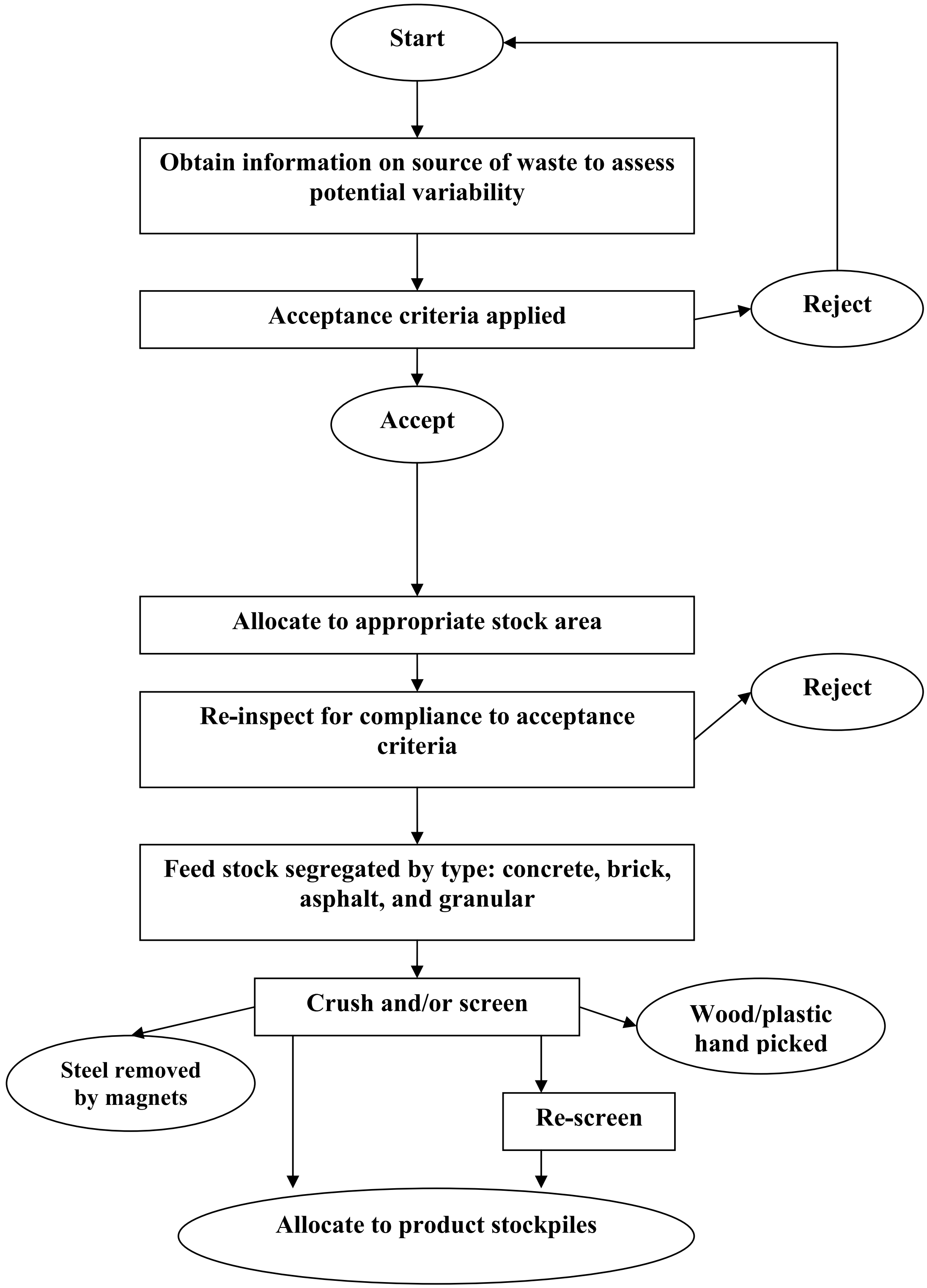

FIGURE B.1: FLOW-CHART FOR ACCEPTANCE AND PROCESSING OF INERT WASTE (www.aggregain.org.uk)

APPENDIX C
AGGREGATE PROPERTIES and TESTING REFERENCES

Aggregate Properties

The following test methods may be used as a means of either deciding or illustrating suitability for a particular end use.

Table C.1: Aggregate Properties and Testing References, (www.aggregain.org.uk)

	ES*	BS EN**	BS*
All end uses			
Particle Density	1109-1971	1097-6	
Los Angeles	1109-1971	1097-2	---
Bulk Density	1109-1971	1097-3	
Use in concrete/hydraulically bound materials			
Water Absorption	1109-1971	1097-6	
Magnesium Sulfate	1109-1971	1367-2	---
Abrasion Resistance	1109-1971	1097-8	
Drying Shrinkage	1109-1971	1367-4	
Chlorides	1109-1971	1744-1	
Sulfate and Sulfides	1109-1971	1744-1	
Alkali Silica Reaction****	---	---	---
Organic Contamination	1109-1971	1744-1	---
Uses as fill			
Water Absorption	1109-1971	1097-6	
CBR	1109-1971	---	1377: Part 4
Plasticity of Fines	1109-1971	---	1377: Part 2
Use as unbound, pipe bedding			
Particle Density	1109-1971	1097-6	
Los Angeles	1109-1971	1097-2	
Plasticity of Fines	1109-1971	---	1377: Part 2
Frost Heave	1109-1971	---	812: Part 124
Water Soluble Sulfate	1109-1971	1744-1	
Magnesium Sulfate	1109-1971	1367-2	
Use in Asphalt			
Particle Density	1109-1971	1097-6	
Water Absorption	1109-1971	1097-6	
Los Angeles	1109-1971	1097-2	---
Abrasion Resistance AAV	1109-1971	1097-8	
Polishing Resistance	1109-1971	1097-8	
Resistance to heat	1109-1971	1367-5	

* According to the Egyptian Code: ECCS 203 for year 2001 and the Laboratory testing manual for 2003.
** According to the British European Standards (www.aggregain.org.uk).
*** According to the British Standards (www.aggregain.org.uk).
**** All RCA must be classed as highly reactive.

APPENDIX D
INERT WASTES

Inert Wastes*

Provided that there is no suspicion of contamination, the wastes listed below are considered to be inert wastes.

Table D.1: Inert Wastes, (www.aggregain.org.uk)

Description	Restrictions
Waste glass based fibrous materials	Only without organic binders
Glass packaging	Selected construction and demolition waste acceptable only with low content of other types of materials (like metals, plastics, organics, wood, rubber, etc). The origin of the waste must be known.
Concrete including solid dewatered concrete process waste	
Bricks	
Tiles and ceramics	
Mixtures of concrete, bricks, tiles and ceramics	
Soils and stones including gravel, crushed rock, sand, clay, road base and planings, and track ballast	Excluding topsoil, peat, excluding soil and stones from contaminated sites
Glass	Separately collected glass only
Soils and stones restricted to parks waste	Only from garden and parks waste; excluding topsoil, peat

* Source: **www.aggregain.org.uk**.

The following definition of inert is taken from the landfill (England and Wales) Regulations 2002 and is included for clarity:

Waste is inert if:

(a) it does not undergo any significant physical, chemical or biological transformations (**www.aggregain.org.uk**);

(b) it does not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm to human health (**www.aggregain.org.uk**); and

(c) Its total leachability and pollutant content and the ecotoxicity of its leachate are insignificant and, in particular, do not endanger the quality of any surface water or groundwater (**www.aggregain.org.uk**).

APPENDIX E
ESTIMATES OF THE CONSTRUCTION WASTE IN EGYPT

Approximate Estimation of the Quantity of Construction waste concrete produced in Egypt[i] per year

- Egypt's total annual production of cement = 36,200,000 metric tons.
- Total quantity of cement exported (approximately) = 5,000,000 metric tons.
- Total quantity of cement consumed in local market = 33,200,000 metric tons.
- Approximate quantity of cement used for structure concretes[j] (assumed as 50% of total cement consumed in the local market) = 16,600,000 metric tons.

Calculation of Construction concrete wastes:

- Density of concrete made of natural aggregates ≈ 2,300 kg/m^3 = 2.3 tons/ m^3.
- Each meter cube concrete contains approximately (1/3 metric ton) of cement = 330 kg cement.
- Estimated concrete waste percentage during construction = 2 to 3%.

Thus, from above: 16,600,000 metric tons of cement (for structure concrete) produces about (16,600,000 ÷ 0.33) = 50,303,000 cubic meters of structure concrete.

Therefore, the volume of concrete waste = 3% x 50,303,000 m^3 = 1,509,000 m^3 as construction waste only[k].

Estimated total quantity of concrete resulting from construction waste only in Egypt = (1,509,000 m^3 concrete x 2.3 tons/ m^3 = 3,470,700 metric tons.

The tonnages of concrete resulting from construction activities in Egypt could be used as a source of coarse aggregate after being well recycled.

Calculation of Conventional Coarse Aggregates Used:

- Density of virgin coarse aggregate (approximately) = 1,600-1,700 kg/ m3.
- Each 1 m^3 structure concrete contains approximately: 1,200 kg virgin coarse aggregate.
- Thus, the approximate quantity of virgin coarse aggregate used annually in Egypt in structure concretes = 50,303,000 m^3 concrete x 1,200 kg = 60,363,600 metric tons of virgin coarse aggregate.
- Therefore, if recycling is done, then we can save about 5.75% of the annual usages of the virgin coarse aggregate (3,470,700 / 60,363,600).

[i] Estimates for year 2006, Source: World Business Council for Sustainable Development (WBCSD) – Website: www.wbcsd.org.
[j] Cement used for finishing works, bricks, blocks and others are not considered.
[k] Demolition concrete waste and other wastes are not considered.

APPENDIX F
EGYPTIAN CODE FOR THE DESIGN AND CONSTRUCTION OF CONCRETE STRUCTURES

Following in Arabic language:

- Tables (2-1) and (2-2): Code number 203, revision 2 for year 2001.
- Tables (2-11-2) and (2-18-9): Code number 203 for year 2003, Annex 3: Manual for laboratory testing of concrete structures.
- Clause (2-17-8): Code number 203 for year 2003, Annex 3: Manual for laboratory testing of concrete structures.

APPENDIX G
PROPOSED SPECIFICATION LIMITS FOR SOME PROPERTIES OF RECYCLED CONCRETE AGGREGATE (in Arabic Language)

الحدود المسموح بها المقترحة لبعض الخواص الفيزيقية والميكانيكية للركام معاد التدوير (Recycled) ومقارنتة بجدول (2-1) فى الكود المصرى

الخاصية	الحد الأقصى المسموح بة فى الكود المصرى للركام الكبير الطبيعى	الحد الأقصى المقترح طبقا لهذة الرسالة للركام معاد التدوير
1- النسبة المئوية بالوزن للمواد الناعمة المارة من منخل 75 ميكرون (منخل رقم 200)	الزلط وكسر الزلط (1%) كسر الحجارة (3%)	لم تحدد (يرجى الرجوع إلى الملاحظات بعد جدول 6.6 فى الرسالة)
2- النسبة المئوية بالوزن للتكتلات الطينية والمواد القابلة للتفتت	3%	2-10 كجم للمتر المكعب (طبقا لجدول 4.9 فى الرسالة)
3- الصلادة معبرا عنها بالنسبة المئوية بالوزن للمار من منخل رقم 1.7 مم بعد 500 دورة تفتت فى ماكينة لوس أنجلوس	الزلط وكسر الزلط (20%) كسر الحجارة (30%)	لم تحدد (يرجى الرجوع إلى الملاحظات بعد جدول 6.6 فى الرسالة)
4- دليل التفلطح Flakiness Index	25%	40%
5- دليل العصوية (الإستطالة) Elongation Index	25%	لم تحدد
6- النسبة المئوية للإمتصاص الطبيعى بعد 24 ساعة	2.5%	7%

الحدود المسموح بها المقترحة للكلوريدات والكبريتات بالركام معاد التدوير (Recycled) ومقارنتة بجدول (2-2) فى الكود المصرى

الخاصية	الحد الأقصى المسموح بة فى الكود المصرى للركام الكبير الطبيعى	الحد الأقصى المقترح طبقا لهذة الرسالة للركام معاد التدوير
1- محتوى الكلوريدات القابلة للذوبان فى الماء Cl^-	0.04%	0.5%
2- محتوى الكبريتات على هيئة SO_3	0.4%	1%
3- ثبات الحجم الكيميائى (معبرا عنة بالنسبة المئوية للفاقد فى الوزن): 3-أ التعرض لـــ5 دورات فى محلول كبريتات الصوديوم 3-ب التعرض لـــ5 دورات فى محلول كبريتات المغنسيوم	 12 18	لم تحدد

<u>الحدود المسموح بها المقترحة لـــ10% ناعم بالركام معاد التدوير (Recycled) ومقارنتة بجدول (2−18−9) فى الكود المصرى</u>

الخاصية	الحد المسموح بة فى الكود المصرى للركام (كيلو نيوتن)	الحد الأقصى المقترح طبقا لهذة الرسالة للركام معاد التدوير (كيلو نيوتن)
خرسانة أرضيات للإستخدام الشاق	لا تقل عن 150	لا تقل عن 150
خرسانة أرصفة	لا تقل عن 100	لا تقل عن 100
خرسانات أخرى	لا تقل عن 50	لا تقل عن 50

<u>الحدود المسموح بها المقترحة لقيمة البرى بإستخدام مكنة لوس انجلوس بالركام معاد التدوير (Recycled) ومقارنتة ببند (2−18−8) فى الكود المصرى</u>

الخاصية	الحد المسموح بة فى الكود المصرى للركام (%)	الحد الأقصى المقترح طبقا لهذة الرسالة للركام معاد التدوير (%)
قيمة البرى بإستخدام مكنة لوس أنجلوس	الزلط (لا تتعدى 20%)	لم تحدد
	كسر الأحجار (لا تتعدى 30%)	لا تتعدى 50% ماعدا للخرسانة المستخدمة فى الطرق تكون لا تتعدى 40%