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# Evaluation of Mechanical Properties of Recycled Aggregate Concrete

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# EVALUATION OF MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE

by

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EVALUATION OF MECHANICAL PROPERTIES OF
RECYCLED AGGREGATE CONCRETE

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The maintenance and repair work in the civil engineering infrastructures develops the production of huge wastes which causes the growth of waste piles, additional costs in construction projects and some environmental problems. If this waste is recycled and used again in construction projects, it will help to overcome the problems discussed earlier. Moreover, if natural aggregates are supplemented by recycled aggregate, it will preserve the natural resources and also put a pause in the deterioration of natural landscape.

This thesis addresses the importance of using recycled aggregate in concrete structures. Its practical feasibility in construction projects is studied in light of the work done by the previous researchers. The concrete mix with optimum amount of recycled aggregate is developed which is further evaluated for the mechanical properties in accordance of ASTM and AASHTO guidelines. Moreover, the optimized mix is evaluated for the benefit to cost analysis. It is then concluded that the use of recycled aggregate in concrete structures is feasible both in quality and cost point of views.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Problem Statement

With the development of new techniques and designs, good aesthetic appearance, remodeling of structures and deterioration causes of varying environmental conditions, repairing and demolishing of structures is on rise as compare to the previous era.

No matter how strongly built, with sufficient reinforcement and other requirements, all the construction applications are exposed to certain environmental and physical elements that cause wear and tear in them. As a result every construction facility has to be repaired periodically or demolished forever. Buildings are sometimes demolished when they are no longer functional, beyond of repair, in the way of some other structures or out of style. With this much repair and demolishing of structure a huge amount of debris are produced every year. Currently in United States, this amount is estimated to be about 200 million tons annually [5].

Certain problems are associated with the debris that is produced during this process of demolishing and repairing. Firstly, as an easy and conventional approach most of the debris produced are dumped in landfill sites, which is another alarming sign that is associated with these waste. Because its amount is increasing with every passing day and in some of the states due to lack of space they are taken to the nearby states. To discourage this trend various state agencies have increased the tipping fees, so that people adopt other alternatives. Secondly, these piles of wastes are affecting environment adversely with no other use but to be dumped there that produce an unaesthetic view. The environmentalists have started lobbying about this solution of construction debris and they have proposed different alternatives to the state agencies that include increase in tipping fees and recycling or reusing of them. Thirdly, it increases the project cost when this material has to be taken through some sources to the landfill site that is additional hauling charges. Most of the landfill sites are in the urban areas and when structures get demolished in rural area and their debris have to be transported to the landfill site, it costs additional money.

This research study is based on recycling of these demolished aggregates, as it is being the only option that will help to overcome all the above mentioned problems. The engineering properties of the recycled aggregate were evaluated during this study in comparison with natural aggregates.

Several benefits were pointed out if aggregate is recycled instead of dumped in a landfill site. They are mentioned below:

- Instead of transporting it to the landfill site, if this aggregate is recycled at site using mobile recycling plant, it will reduce and in some cases will eliminate the additional hauling charges. As a result projects will not get costly
- In areas where natural aggregate is scare and currently is obtained by degrading the natural landscape, the option of recycling will reduce this factor and the natural landscape will remain as it is
- It also conserve the natural aggregates when after recycling is used as supplement to them
- It will eliminate the production of stockpiles of waste materials that are located in several areas right now

- This option of recycling aggregates is a good way to redirect a stockpile of waste into a resource

## 1.2 Research Objectives

The objectives of this research study are listed below:

- To study the feasibility of recycled aggregate in construction. For this purpose literature search for the values of different engineering properties of concrete using recycled aggregate as coarse material with comparison of concrete with conventional natural aggregate
- Based on the literature search and evaluation criterions, selection of optimized proportion of recycled aggregate in concrete
- Evaluation of mechanical properties of the optimized concrete mix and its comparison with other conventional concretes
- Conduct a benefit cost analysis of recycled aggregate based on unit production cost, benefits to costs ratios and its comparison with natural aggregate

## 1.3 Research Methodology

Main objective of this research study is the evaluation of mechanical properties of the optimized concrete mix. These objectives will be achieved through the extension of the following tasks:

- Phase one of the study is the optimization of the concrete mix. It is the optimum proportion of recycled aggregate with the least effect on other properties of concrete. Several proportions of recycled to virgin aggregate were used in concrete. They were further evaluated under the criterion of workability and compressive strength. The proportion that gave the best results of all was chosen as optimized mix

- Phase two is the further investigation of the optimized concrete mix. In this phase, the optimized mix was evaluated for mechanical properties. The results were compared with those found in literature review and other concrete mixes.
- The third phase is the benefit cost analysis of recycled aggregate. After getting satisfactory results from the previous phase, the unit production cost and benefit to cost ratio of recycled aggregate were calculated in this phase. Its findings are compared with natural aggregate.

## 1.4 Research Layout

Based on research objectives and keeping in view the research methodology, the layout for writing the findings of this research study is as follow:

Chapter two is based on the thorough literature search about the objectives of the study. It explains the current use and recycling of aggregate, values and results of several experiments and engineering properties throughout the world in general and in the United States in particular. It also tells about several demonstration projects and the progress made with use of recycled aggregate in several countries.

Chapter three explains the laboratory work carried out to select the optimized amount of recycled aggregate. Several concrete mixes were produced and were evaluated for their behavior both in fresh and in the hardened stages. In the fresh stage the workability of the concrete was observed and compared to the designed values while in the hardened stage the samples were tested for compressive strength, after they were allowed to develop enough strength.

Chapter four is about the further investigation of the mechanical properties of the optimized mix. In this chapter, the optimized mix was evaluated for some important tests in accordance with ASTM and AASHTO specifications. The results were compared with the results of the work done by previous researchers on the same topic and to the conventional concrete.

Chapter five is the discussions and findings of the cost factor of recycled aggregate. After achieving satisfactory results during quality evaluation, cost to benefit analysis of recycled aggregate were determined. The cost parameters were obtained during the site visits and benefits to cost analysis were calculated both for recycled and natural aggregate. Unit production cost and benefit to cost ratios were calculated and the results were compared.

Chapter six is about the guidelines for using recycled aggregate concrete which are developed during observation and literature through out the research study.

Chapter seven explains the conclusions drawn in different phases during this research study. Limitations, contributions of the research and recommendations for future work are also included in this chapter.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Maintenance and repair work is the normal practice in most of the nation's infrastructure. As a result, production of a huge amount of debris is produced. At the beginning, this demolished material had to be land filled with no other option available. With the passage of time the effect on environment, concerns with this accumulation of debris were realized and alternatives were sort out. Recycling of this debris to make them useable again was one among them. It preserves natural landscape and resources. It also prevents the formation of piles of debris and helps keeping environment clean.

This practice of concrete recycling is gaining importance, because it protects natural resources by substituting them and eliminates the need for disposal when they are obtained during maintenance or repair work.

Recycling of aggregate is a simple process. It involves breaking, removing, and crushing of the concrete into a material with a specified size and quality. But this processing affects the further use of the aggregate. For example, if it is required in backfill, no especial treatment is required but if it is intended to be used in some quality work, care is needed to be taken while processing or recycling this material. Like, 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 and clay balls, chlorides, glass, gypsum board, sealants, paper, plaster, wood, and roofing materials which can be troublesome.

After developments in the techniques and recycling or crushing facilities, up till now, concrete wastes, which were used as roadbed or back-filling materials, can be used as many times as necessary as aggregates for concrete, contributing to the recycling of materials for construction work.

## 2.2 Recycled Aggregates Concrete (RAC)

Aggregates are mainly defined as materials either in natural, manufactured, or recycled forms that are mixed with a cementitious material to form concrete. They can also be treated alone to form products such as railroad ballast, filter beds, fluxed materials, or filling material [9]. They are particles of rock or recycled materials used in combined form with other materials or unbound as part of an engineered structure. They are composed of rock fragments that may be used in their natural form or after recycling through processes when intended for reuse.

The terms “Recycled Aggregate” and “Secondary Aggregate” are often used interchangeably. The “Recycled Aggregates” are those that have been used previously in construction only. It can be comprised of construction and demolition (C&D) debris, asphalt, road planning, and used railway ballast. “Secondary Aggregates” on the other hand, are by-products of other processes and would not have been used previously as aggregates. They include colliery spoil, china clay waste, slate waste, power station ashes, blast furnace, steel slag, incinerator ashes, and foundry sands[7].

Recycled aggregates are produced from reprocessing of old or used concrete, with the largest source being construction, renovation, and demolition waste. During this process of crushing, desired aggregate size can be obtained. This process is called recycling and aggregate obtained during this process is known as recycled aggregate. To make this process more economical and practical, crushing plants can be established on-site.

When infrastructures reach the end of their lives, or because of other reasons, they have to be demolished or renewed. During demolition, used concrete can be crushed into a coarse granular material of any desired size and can be used as a substitute for crushed natural aggregate [28]. If it is then desired to recycle this demolished material, it is transported to the crushing or recycling plant. After recycling, it can be used in construction applications again. Due to ease in the processing and handling, aggregate users are beginning to accept recycled concrete. It is beneficial to document this whole process of recycling. This whole process is demonstrated in Figure 1.

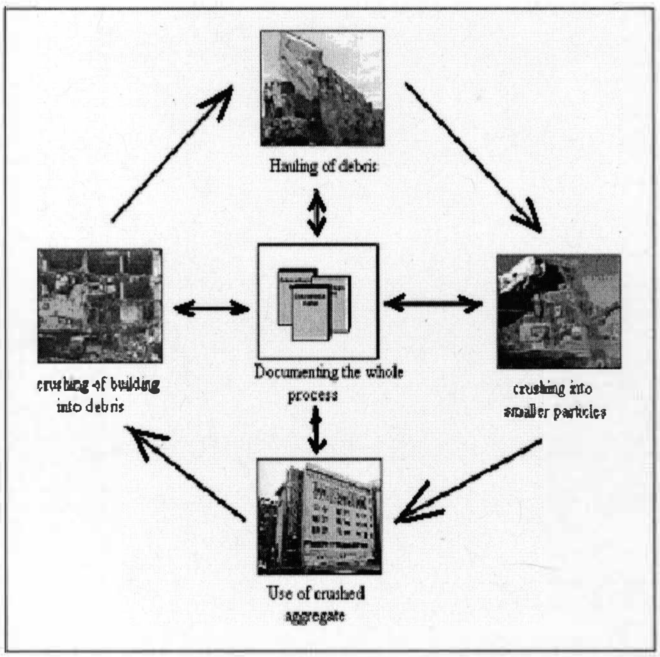



Figure 1: Different Stages in Recycling Aggregate [23]

A significant proportion of the construction, renovation, and demolition waste are produced by Portland cement concrete (PCC), which produces recycled concrete aggregate. It has been found superior in performance to natural aggregates in some applications [10], like areas where high compaction is required or where structures are exposed to a varying weather conditions. In some applications, RAC produced only from the crushing of used concrete has been graded as a higher quality aggregate than that produced by construction renovation and demolished waste.

It is important to select the appropriate demolished material to be recycled while keeping in view the target usage application of it. Figure 2 shows the general layout of aggregate to be used in the first application and the different stages the aggregate goes through until it is made usable again.

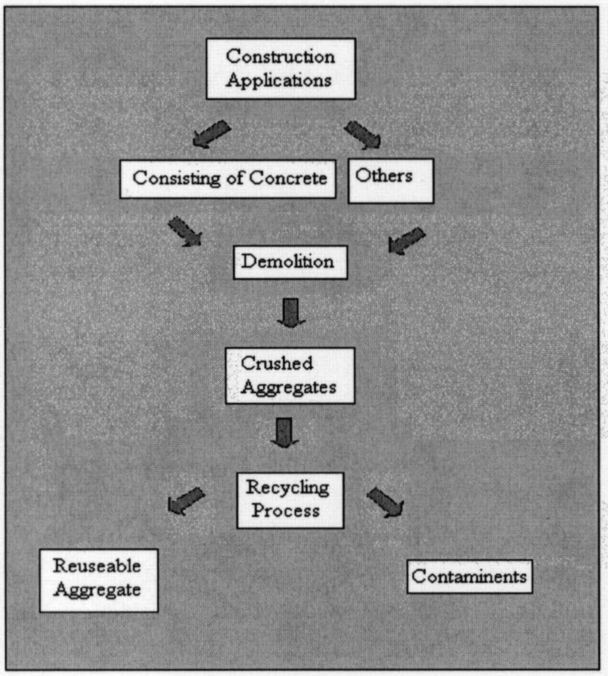



Figure 2: Derivation Process of Crushed Aggregates from Different Sources [29]

Looking at the whole cycle where natural aggregates are derived from natural deposits through different sources in the form of crushed stone, sand, and gravel. After passing all tests, it is used in concrete and then in structures. When these structures go out of date or due to certain other reasons they are to be demolished or renovated, the resulted debris are recycled and used again. The whole process is shown in Figure 3. Vertical arrows show losses to the environment, which occur throughout of the process.

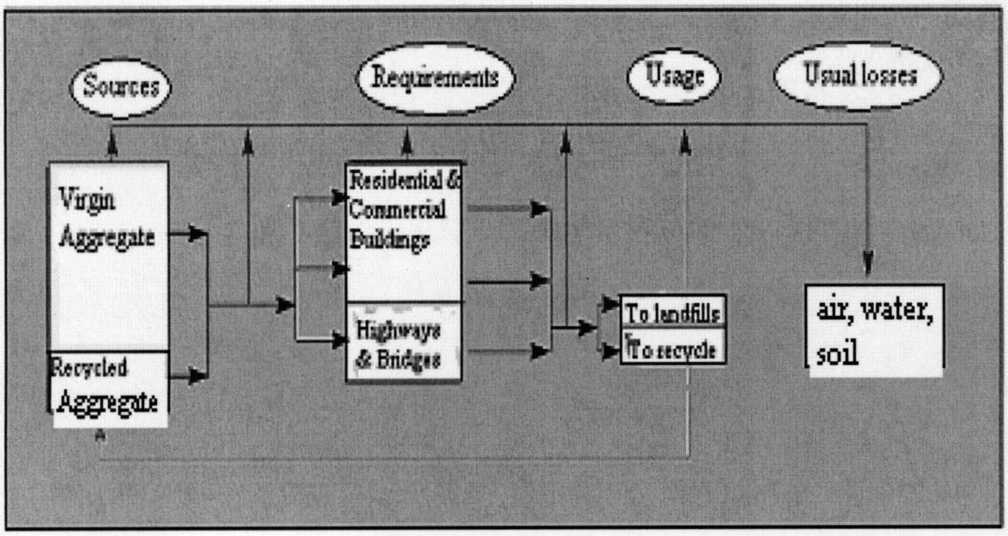



Figure 3: Natural & Recycled Aggregate Flow in Construction [9]

## 2.3 Current Market

Old concrete and masonry that have reached the verge of useful life can be recycled and used not only as aggregate for new concrete, but also for a number of other applications in construction. There are no longer any barriers to use recycled aggregate in new concrete in the United States. The U.S. Army Corps of Engineers and the Federal Highway Administration (FHWA) also encourage the use of RAC in their specifications and guidelines[32].

One of the reasons government and construction agencies are encouraging the use of recycled aggregate is that there is an increasing political and ecological opposition to the production of sand and gravel because it is obtained by dredging huge cavities in the traditional landscape. Using the same process, most of the aggregates in Florida are obtained from the available natural landscapes. These aggregates consist of crushed limestone mined mainly in the southern part of the state. These mines are the source of several million tons of aggregate each year, scarring the natural shape of the land permanently. The resulting pits can be taken over for recreation as they fill with water, which is one of the alternatives. Yet, further exploitation of this kind is no longer acceptable considering increasing urbanization and the growing public concerns of people and environmentalists.[38] It is therefore suggested for urban areas where landfill space is scarce, dumping concrete is expensive and hard to get to crush the old concrete for reuse.

Solving some of the above stated problems, recycled aggregate can also be used for many purposes, but the current primary market is road base, where it is used as aggregate base [21 & 26]. It is also used in other low load bearing areas in certain construction applications. In addition to roadways, designers and other construction-related professionals suggest its use in sidewalks, curbs, bridge substructures and superstructures, concrete shoulders, median barriers, residential driveways, erosion control, general and structural fills. It can also be used in subbase and can support layers such as cement-treated bases, un-stabilized bases, and permeable bases. Apart from these, oversized material can be used at entrances of construction sites to help remove mud from tires of vehicles [23].

The ongoing use and research proved that recycled aggregate has the potentials. It can therefore be stated that concrete recycling is a great success. Apart from reducing disposal of concrete and asphalt rubble in landfills, it has also created a source of low cost aggregate. This aggregate has shown satisfactory results in a variety of projects. These projects, which are described in detail later on, have been durable and cost effective, which are the two main objectives of any construction.

With the exception of certain limitations, RAC has proven to be of good quality. Showing satisfactory results in different laboratory tests, it is now concluded globally that RAC can be a good alternative to natural aggregate concretes. In areas where natural aggregates are costly or not readily available for use, recycled aggregate can be used as its supplement after recycling it into a useful material, instead of dumping it off in landfill sites. Comparing the hauling costs, plus the actual expenses of natural aggregates to recycling the readily available old concrete and its recycling cost, it is better from an engineering point of view to use RAC [11].

The use of RAC in highways is a big achievement of the research done for this material. The next step is to evaluate it for use in load bearing structures, which will need establishment of specifications. Different scholars, institutions, and national and international construction organizations are working on it. Though it has been used in some projects in some countries, it has not yet gained widespread acceptance in concrete and asphalt production in most of the countries including United States.

Recycled aggregate is used in different parts of pavement systems, like crushed aggregates are used as subbase and base layer for surfacing low traffic or temporary applications. Its use also improves unstable sub grade materials. Some of the significant aggregate characteristics of these applications are as follows [8]:

- Base layers – Its primary considerations for a base coarse are support characteristics and durability.
- Surfacing – Recycled aggregate is used for surfacing of temporary roads or for low traffic applications such as local, county, and medium sized roads or private parking

lots. Stability, dusting, and resistance to rutting are primary considerations for surfacing materials.

- Subgrade stabilization – Problems related to subgrade in local areas are mostly solved when recycled aggregate is used. The primary consideration of recycled aggregate as subgrade is its ease in compaction. Due to variation in its sizes, it is also useful for supporting and expanding the axial loads equally.

Recycled aggregate is also used as bedding material in utility installations, which serves several purposes. For example, it makes the bedding compact easily around pipes and other features. The bedding also bears and distributes loads from pipes or other conduits. In addition, the bedding also provides lateral support for other materials like plastic pipes [8]. It is also used in shoulders, porous fills, and in limited quantity in concrete for rigid pavements [40]. To increase the use of RAC in new pavement construction and other applications, the characteristics of RAC have to be well understood and documented with firm rationale and long term standards. It is therefore a challenging job to introduce a new material, like application of recycled aggregate in load-bearing structure applications. It is also important to justify all the objections and barriers.

## 2.4 Barriers in RAC

The recent research about RAC and its practical use proves it a tremendous success. But its use is still limited, and further work is needed to enhance its use in other applications. There are still some barriers in the way of RAC which limits its successful use, but with current ongoing research the potentials in RAC will be revealed very soon. One of the keys that are suppressing the qualities of recycled aggregates is information.

An information network connecting demolition sites, treatment plants, and reusable sites is essential in order to help minimize the cost of transportation and storage.

The barriers and demerits which limit its use are listed below:

### 2.4.1 Lack of Suitable Laws

Government agencies are trying to increase the use of RAC by applying different taxes on natural aggregates. It encourages research and use of RAC which is required for long term sustainable use of RAC. But in some cases, state agencies made hurdles in using RAC. In at least three reported instances, concrete recycling has been stopped by officials. They were concerned about lead-based paint being part of the concrete stream. Tests in all three cases showed the level of lead present was acceptably below the allowable EPA standards; however the officials would rather see it to go to a landfill [13]. Therefore, the government should establish certain constant regulations regarding the use of RAC before contractors start working, rather than interrupt them later on, slowing the work and increasing project costs.

### 2.4.2 Lack of Codes, Specifications, Standards and Guidelines

In most of the materials, characteristics and specifications are accepted if a slight change occurs in its primary structure design. Similarly, if a concrete, using a slightly different material but having the same characteristics as ordinary concrete, the material will be accepted [1]. Small changes may be covered by modifying details of the design, quality control, and concreting in-situ. However, in many cases the use of RAC or other materials cause non-negligible changes in the concrete characteristics which cannot be compensated by a small change in the design detail [32]. It should also be noted that a tiny mistake or self-designs could cause a huge disaster. In these cases, changes must be made to the entire design of the structure or concreting method, however this is not accepted in most of the construction projects. So, it is necessary to have separate specifications and design methods when dealing with such types of materials in construction [1].

### 2.4.3 Cost

The general concept about concrete recycling is that it costs much more than acquiring and using natural aggregates due to quality variation, energy, and significant costs [13]. This fact can be accepted for the areas where it is hard to establish a mobile crushing plant or if natural aggregates are available nearby and at reasonable prices. But it is useful to recycle aggregate where case is not as above. This misconception needs to be cleared, which needs a lot of factors, including research, demonstration projects and support of government agencies. Researchers have also proved that, it costs 20% to 30% [32] less to use recycled aggregate than natural aggregates. Some research identifies savings of 50% to 60% [32]. So comparing the cost of crushing plant on site to the hauling charges of natural aggregates with net charges, it is economical to use RAC.

### 2.4.4 Poor Image

Generally, waste is considered to be either of low quality or useless material. This might be true, but lately researchers have tried to find means and ways to recycle and reuse the waste [1]. The present research and technological advancement has made the recycling of waste almost inevitable.

### 2.4.5 Lack of Experience

When new materials or construction methods are introduced, experience is required in order to ensure safety of the overall project. The entire image of the construction company depends on its safety management and completing the project with minimum or no injuries. Since recycled aggregate is new material as compare to other aggregates. It therefore lacks experience, which ultimately causes lack of confidence and therefore most of the contractors and construction firms hesitate to use recycled aggregate.

### 2.4.6 Low Quality

General concept about recycled aggregate is that it is of low quality as compared to virgin aggregate. It makes sense that there is always a difference between the used and new material. However, for concrete materials, if it is proved through laboratory tests that materials of different ages show positive results with the introduction of additional materials like fly ash, silica fume, or fibers, used materials can give same results.

Improvement or enhancement in the quality of recycled materials leads to improvements in technologies. For instance, machines for processing recycled aggregates from demolished concrete have been replaced by newly designed crushing machines. Recently, new types of processing machines have been developed which enable even higher quality recycled aggregate by sieving and crushing it into the desired sizes with lower energy consumption.

### 2.4.7 Variation in Quality

Because of different types of structures with different ages and ratios of concrete, the quality of demolished concrete varies from structure to structure. Also most of the recycling plants are small and lack large stock yards. These facts cause variations in the quality of aggregates from recycling. This variation in size has some benefits like easily compaction but it also requires frequent quality control testing and may cause quality concerns about the final project, if were not taken care of. Easy and frequent quality control test methods could be more effective when dealing with recycled coarse aggregate. Apart from these problems, concrete obtained from demolished structures has already passed some quality tests too, so it is easy to eliminate some settings when dealing with demolished concrete materials.

### 2.4.8 Lack of Proper Market

Lack of specification codes, communication gaps, insufficient equipment, low advertisements, and use in low quality applications are some of the areas that limit use of RAC. Proper coverage, strong demonstration projects, and laboratory tests will further help to enhance its quality, durability, current market, and poor image.

## 2.5 Merits of RAC

The growing trend in the research of RAC predicts that this material has some benefits, causing people to think about and perform research.

It is also important to use the aggregate which is cleaned from undesired products. For instance, the use of waste or recycled glass as aggregate for concrete will break the closed loop, which obviously affects the durability of the final project as compared to normal concrete. Though it is a hard job to separate such materials that get mixed while recycling but it is possible. If they are not separated the lifespan of the structures will get shortened. Considering the future of the structures where glass or other materials have been used as aggregates in concrete, they have no use when they are demolished in the future again. Use of such materials will affect the process adversely. So, in long term planning, such materials should be avoided in aggregates.

The use of recycled aggregate can also save money for local governments and other purchasers, create additional business opportunities, save energy when recycling is done on site, conserve diminishing resources of urban aggregates, and help local governments meet the goal of reducing disposal to landfill sites.

During literature review, this fact came to the surface that recycled aggregates have been used in infrastructure for several years now and is gaining global acceptance and positive responses. Being one of the products that have benefits from both economic and environmental standpoints, it can be helpful in reducing disposal costs and also the cost of new aggregate on infrastructure projects. It will also reduce the unlawful disposal problems and conserve limited available landfill sites. It is most likely that recycling aggregate will be successful in areas where transportation dynamics, disposal, tipping fee structures, resource supply/product markets, and municipal support are favorable.

Benefits obtained using recycled aggregate in concrete can be summarized in three main categories:

### 2.5.1 Engineering Benefits

Engineering qualities always play an important role in the design, and long term durability of all the construction projects. Seeing importance of this quality, researches and surveys have proved that RAC has some engineering advantages that are considered by most concrete engineers while designing any kind of construction project. Some of them are described below:

- Concrete made with recycled aggregate is economical and will not grow or expand with moisture [20].
- RAC in new concrete decreases the resilient modulus and increases the creep [20]. These changes are advantageous in the areas creep or shrinkage is not an issue, like water channels or gravity concrete drains.
- Concrete mixtures which incorporate recycled aggregate show good freeze-thaw durability characteristics [9]. So, this aggregate can prove beneficial in areas of varying atmosphere.
- The aggregate particles of recycled aggregate compare well to natural aggregates in that they possess good particle shape, high absorption, and low specific gravity.
- Recycled aggregate concrete has shown no significant effect on the volume response of specimens to temperature and moisture effect.
- RAC that originated as concrete with rounded aggregate yields a new product with particles having fractured angular shapes when it is reused [32], which increases past bond.
- Recycled aggregate compacts up to two to three times faster as compared to natural aggregates [9]. That increases durability of highways when used in road base.
- Use of recycled aggregate as a lone cementitious material improves the strength in different applications of highways [32], and its usage has shown better performance

compared to natural aggregates in several applications, where high strength is required [9].

- Damage to any infrastructure can be fixed due to the proximity of a crushing plant. RAC is therefore helpful when an urgent repair is required [20], particularly in highway works.

### 2.5.2 Economic Benefits

It is one of the key properties of any construction project to be as much economical as possible without affecting the overall durability, quality, and safety of the project. So, while using RAC, if it is not affecting the durability, it should be considered for making construction projects more economical.

Most municipalities impose tight environmental controls over opening new aggregate sources. It is therefore an attractive option for governmental agencies and general contractors alike.

- Recycling gives another direction to construction waste when it is used as useful material.
- Recycled concrete is 10% to 15% lighter in weight [20]. This results in low costs for labor and transport.
- In some cases even 100% recycled coarse aggregate produced acceptable quality concrete [32], which reduced the costs of the project remarkably.
- Waste usage within the same area decreases the hauling distance, which is one of the most costly expenditures in construction.

- To encourage the use of recycled aggregate, some state authorities have established an income tax credit on the purchase price of aggregate recycling machinery. Buying these machines at low costs, will also lead to make the projects economic.
- RAC is more economical in urban areas. This is attributed to the lower cost and higher yield per ton of RAC compared to natural aggregate, along with lower cost and ease of handling.
- In areas where natural aggregates are not readily available or are more costly, recycled aggregate is the best supplement.
- The proximity to metro areas of RAC crushing plants makes it economically attractive for commercial uses in base, other applications, and especially parking lots.

### 2.5.3 Environmental Benefits

In the current situation of increasing attention to the environmental impact of construction and sustainable development, RAC has much to offer.

- For aesthetic sense with the use of RAC, the development of huge waste piles of demolished debris will be reduced by a large quantity [20].
- Recycling on site will reduce the haul distances, reduce energy consumption and will help improve air quality for a better environment through reduced mobile source emissions [20].
- The use of RAC also provides other means to recycled concrete rubble, which can be used in many areas of construction.
- RAC results in preservation of natural aggregate resources [32]. As a result, stockpiled material in rural areas will be available for the metro areas.

- Ready mix industry suggested that with the development of recycling of hardened, waste, or by-products from the process, the concrete plant will become a no-waste facility.

## 2.6 Demerits of RAC

Despite of all these advantages, this material does have some demerits:

- Due to its contamination with gypsum plaster, recycled aggregate obtained from a demolished concrete site has the risk of high sulfate content. This presence of sulfate and/or gypsum can produce expensive reaction.
- Another problem with using RAC in concrete production is its ability for alkali-silica reaction with alkaline water. This reaction results in a product that causes cracking and overall deterioration of the concrete mixture.
- Recycled aggregates are often comprised of different sized materials with highly variable properties, which can causes problems in the mix designs.
- Laboratory results have shown that depending upon the proportions of recycled aggregate the strength values of concrete are reduced remarkably. These values are estimated to be decreased by about 15% to 25% [32].
- To determine suitability, it is important to evaluate recycled aggregates on a project by project basis.
- The presence of chlorides in the aggregates obtained from cold areas has the ability to react with the admixtures in new concrete and can cause changes in setting behavior.
- RAC has less density than concrete of natural aggregate.
- Tests have shown that RAC requires extra water while mixing designs, which proves that RAC is low workable as compared to natural concrete aggregates and if not

considered at SSD condition, it can changes the amount of mixing water in concrete also. Extra water may cause high shrinkage.

- The damping capacity increases by 30% [9] when natural aggregate is substitute with recycled aggregate.
- With an excess of recycled aggregate amount in a mixture, the values of toughness, plastic energy capacity, and elastic energy capacity decreases [9].

## 2.7 Factors Affecting Recycling

- For the economic success of the project, it is important to minimize the distances and communication between recyclers, suppliers, construction sites, and markets. In one of the scenarios shown in Figure 4, if all the alternatives are available, alternate C should be the best choice. It is because of the proximity to the demolished structure and construction site.

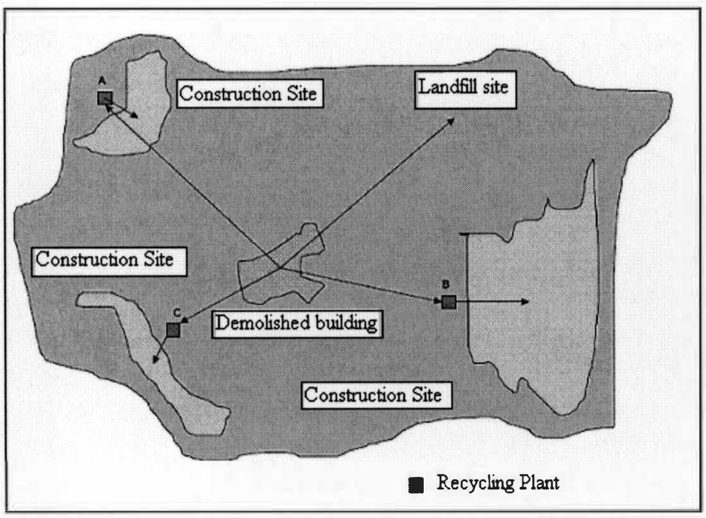



Figure 4: Feasible Location of a Recycling Facility [9]

- Transportation distances and costs are a significant part of the dynamics that define the use of construction aggregates within a region, but they normally do not affect operational profitability of the recycler directly because costs for transportation are typically incurred by the contractor of the project. So for contractors' point of view, while recycling the demolished concrete for aggregate to be used in concrete, it should be preferred that an on-site crushing plant be established. That is why in the United States most of the plants are mobile rather than stationary.

- Production cost of recycled aggregates depends on several elements:
    - Capital expenditures, type, size, and other related equipment in the plant
    - The availability of production and maintenance skilled man power
    - Availability or location of water facilities
    - System of power supply
    - Legal ways of acquiring land for recycling operations
    - Type and source of demolished materials to be crushed
    - Removal of contaminants, present in aggregates
    - Operating supplies and utilities
    - Taxes, insurances, depreciation, permit costs, and other local fees
- A complete success story of the aggregate recycling industry cannot be presented without considering the influence and effect of government policies on this sector. Social concerns for the environment have also resulted in increased emphasis on promoting a more sustainable use of natural resources in recent years. Recycling is considered to be one program contributing to such a goal.

## 2.8 Engineering Properties of RAC

The crushing characteristics of hardened concrete are similar to those of solid natural rock and are not significantly affected by the grade or quality of the original concrete. But concrete containing recycled aggregate has been found to have some different physical and mechanical properties than concrete containing natural aggregate. It is therefore important that recycled aggregate produced from all original concrete should have to pass the same tests required for virgin aggregates [32] before using it as coarse aggregate in concrete intended for any kind of structure.

### 2.8.1 Strength

Laboratory tests have shown that concrete composed of recycled aggregates are weaker in strength as compared to concrete with virgin aggregate. Further it has been found that concrete containing recycled aggregate, up to certain limits, has 25% [32] less strength than those comprised of virgin aggregate. It also causes up to 30% [9] improvements in damping capacity. Furthermore, concretes with recycled aggregate generally are expected to develop about a 10% lower flexural strength at equal water cement ratio and slump than natural aggregate concrete [31].

During literature review it was found that due to much importance, strength of concrete has been evaluated in most of the studies and a lot of research studies were found that worked on strength of concrete exclusively.

In one of the recent studies by New Jersey Department of Transportation (NJDOT), it was found that compressive strength of concrete decreased when proportion of recycled aggregate was increased. Comparisons of compressive strengths of concrete for different proportions of recycled aggregate and some properties of hardened concrete are shown in Table 1 [19] and Table 2 [40, 60].

Table 1: Compressive Strength for Concrete Containing Different % of RAC

| Proportion of RAC | Curing period (days) | Compressive strength (psi) | Average compressive strength (psi) |
|---|---|---|---|
| 0% | 14 | 4935 | 5377 |
| | 28 | 5465 | |
| | 56 | 5731 | |
| 50% | 14 | 4326 | 4660 |
| | 28 | 4824 | |
| | 56 | 4830 | |
| 100% | 14 | 3786 | 3930 |
| | 28 | 3769 | |
| | 56 | 3933 | |

Table 2: Properties of Hardened Concrete Containing RAC

| Proportion of RAC (%) | Compressive strength (psi) | Tensile strength (psi) | Flexural strength (psi) | Modulus of elasticity ($10^3$) (psi) |
|---|---|---|---|---|
| 0 | 6220 | 374 | 748 | 5170 |
| 25 | 5730 | 373 | 724 | 4850 |
| 75 | 5520 | 365 | 653 | 4640 |
| 100 | 5070 | 358 | 604 | 4420 |

### 2.8.2 Gradation

Demolished debris intended to be recycled to get coarse aggregate, normally contains a huge amount of fine materials. It is mainly due to the demolishing process which mixes all the materials and creates a huge amount of powdery debris. Without sieving, this material will make the concrete drier and will require an extra amount of water or other materials to make the concrete workable.

Concrete to be recycled should be crushed and screened to produce aggregate that satisfies the standard gradation curve, AASHTO M43 requirements for the size number specified [15,] or M6 and M80 gradation requirements for PCC [31]. Most of the researchers had followed it that recycled aggregate was sieved and used in laboratory tests after it fell under the standard gradation curve [35 & 37]. With the introduction of new machines, this problem has been solved up to some extent. Now, depending upon the type, and with slight adjustments in the crushing plant, reasonably well-graded recycled aggregate can be produced to meet ASTM and AASHTO gradation specifications. Furthermore, for more safety, engineers should call for all requirements for recycled concrete coarse aggregate as they would for natural aggregates accordingly.

### 2.8.3 Particle Shape

Recycled aggregate is found to be very angular in shape [31]. This quality assists in increasing strength when compacted properly, but results in workability reduction. It is similar to crushed rock in particle shape. If desired, demolished plain and reinforced concrete can be crushed in various types to provide recycled aggregates within acceptable particle shape. It is however feared that type of crushing equipment will influence the gradation and other characteristics of crushed concrete.

### 2.8.4 Specific Gravity

The specific gravity of RAC from different sources may have variation [15]. The main reason for this variation is the old mortar and cement paste adhering to the old aggregates. It had shown specific gravity of 5% to 10% [31] lower than that of natural aggregates. Typical values of specific gravity of recycled aggregates were found to be in the ranges of 2.2 and 2.5 in the saturated surface dry condition [31, 32].

### 2.8.5 Water Absorption

Absorption quality of recycled aggregate is high as compared to natural aggregate. It is mainly because this aggregate has been prone to different environmental conditions for certain time. Also the large amounts of old mortar and cement paste that get stuck to the demolished concrete, changes its properties from original one [15]. But still depending upon the source of aggregate, this value varies too. It has been found within the range of 2% to 6% [32]. Pre-soaking of recycled aggregates is therefore recommended to help maintain the uniformity of absorption during concrete production. It is also important to take this property in consideration during mix designs; otherwise higher absorption value will adversely impact concrete workability.

Physical properties found during search are shown in Table 3 [31, 40 & 41].

Table 3: Properties of Recycled Aggregate Concrete

| Parameter | Ranged Values |
|---|---|
| Specific gravity (SSD) | 2.00 to 2.64 |
| Water absorption (SSD) (%) | 1.33 to 8.00 |
| Unit weight ($kg/m^3$) | 1410 |

### 2.8.6 Permeability

Recycled aggregate is a free draining material. It is more permeable than natural aggregate [15]. Its use in the areas where structures are exposed to water is therefore not suggested, like sewage and water supply pipes, water channels and under water structures.

### 2.8.7 Moisture Content

The in-situ stockpile moisture content for crushed recycled aggregate is almost the same as that for natural aggregates [41]. Some researchers say it is slightly over than the natural aggregate [31].

Some values for moisture content and density found are shown in Table 4 [41].

Table 4: Particle Properties of RAC

| Parameter | Ranged Values |
|---|---|
| Moisture content (%) | 9 to 12.8 |
| Density (g/cm$^3$) | 1.81 to 2.21 |

### 2.8.8 Durability/Abrasion Loss

Recycled aggregate performs well in soundness characteristics and abrasion resistance. This property of concrete is important when it is used in pavements and floor slabs. The abrasion loss for recycled aggregate concrete is found to be in the range of 20% to 45% [32]. The upper limit is 50% for pavement aggregate [41].

### 2.8.9 Sulfate Soundness

Sulfate soundness determines the weathering resistance of the concrete. It is therefore an important factor in the areas, having variation in weather. When tested for soundness using sodium or magnesium sulfate solutions, it resulted in higher than expected soundness loss values. Recycled aggregates in the limits of 12% (for Sodium) and 18% (for Magnesium) [15] are considered to have good soundness.

Depending upon the source of recycled aggregate, this value is needed to be taken care of, which is found to be more susceptible to sulfate attacks. If tested properly, it is found to be satisfactory if the recycled concrete was durable in its previous life and is recycled properly. Values of soundness loss for recycled aggregates in the United States conflict with those of other European countries [32].

### 2.8.10 Alkali-Silica Reactivity (ASR)

Experiments have shown that recycled aggregate has higher tendency towards alkali-silica reactions when exposed to alkaline pore water as compared to virgin aggregates. It was determined in an investigation that the potential of ASR in new concrete was affected by the old concrete's original alkali level, extent of expansion, and the remaining potential reactivity of crushed coarse recycled aggregate. The research also demonstrated that with appropriate selection of cementitious materials, even recycled aggregate containing highly reactive aggregate can be used safely. Assessments showed that potential of ASR in concrete produced with RAC is complicated by the alkali contribution of the RAC to new concrete mix [10].

### 2.8.11 Creep Analysis, Shrinkage, and Resistance to Freeze-thaw

During literature search, no solid laboratory test results were found for any of these mechanical properties for RAC. It was quoted however; that concrete comprised with recycled aggregates has high tendency towards creep and shrinkage. It was because of some of the properties of RAC, like high porosity, water absorption, and decrease in density, there was an increase in the shrinkage and creep[54]. It was also found that results in resistance to freeze-thaw were satisfactory, provided a suitable air void system is present in the mortar stage of concrete [15].The properties of recycled aggregate, its comparison with virgin in percent values and its effect concrete are shown in Table 5.

Table 5: Properties of Recycled Aggregate (RA)

| Property of RA | Comparison with virgin aggregate | Changes by approximate value | Effect on concrete |
|---|---|---|---|
| Strength | Low | 25% | Low durability |
| Damping | High | 30% | |
| Gradation | Finer | | water or water reducer |
| Particle shape | More angular | | Increase in strength & reduction in workability |
| Specific gravity | Low | 5% to 10% | |
| Water absorption | High | | Additional water |
| Permeability | High | | Limits use in structures exposed to water |
| Abrasion loss | Low | 20% to 45% | Use in areas under load |
| Creep & shrinkage | High | | Deterioration in hardened shape |
| Resistance to freeze & thaw | High | | Use in varying weather conditions |

## 2.9 Deleterious Substances

The need for predictable and consistent performance from the final product produced is one of the factors limiting the reuse and recycling of construction and demolition waste. Another problem inherited by recycled aggregate is the possibility that contaminants may pass into the new concrete with the original debris having unfavorable effects on strength and durability [39].

Some of the usual contaminants and their limited amount in recycled aggregates are listed as:

### 2.9.1 Bitumen

The presence of asphalt in aggregates reduces the strength of concrete and ultimately of the area of construction where it is intended to be used. It can be estimated from the fact that the addition of 30% by volume of asphalt to recycled aggregate can reduce the compressive strength of concrete by about 30% [39]. So, in order to keep the designed and desired strength while using RAC, amount of asphalt particles should be limited to the value that does not do any harm to the strength. Some researchers have suggested this amount not be more than 5% by mass [11].

### 2.9.2 Mortar

The quality of demolished debris depends upon the type of bricks and the quality of mortar used earlier. It is because when structure is demolished, mortar gets stuck to bricks or cement blocks. They can be removed easily from the demolished brick, which can further be used as second hand brick, but cement-containing mortar is more difficult to remove or separate. With no other option, the types of bricks or quality of cement blocks that got stuck to mortar are often crushed into aggregates but recycled concrete aggregate should not contain more than 5% crushed brick by mass.[11]

### 2.9.3 Organic Matters

Some organic substances like paper, wood, fabrics and other polymeric materials are mostly volatile and they evaporate when concrete is exposed to freeze-thawing and drying. If concrete has some lead paint, it can also cause entrainment of huge amounts of air in concrete. These organic impurities are relatively light in weight but have a tendency to increase in large amounts. To avoid such actions, recycled concrete aggregates should be free of them and all other materials that fall under the solid waste or hazardous materials category, as defined by the state or local related departments.[11]

### 2.9.4 Chlorides and Sulfates

Reinforced concrete is more prone to corrosion due to salts. Chlorides and sulfates are the main causes for corrosion to steel, when they react with concrete. It is therefore found that they do not have significant effects on concrete without reinforcement. But still when large amounts of sulfates are entrained in concrete, they react with cement compounds and cause excessive expansion and ultimately deteriorate the hardened concrete. Because of the harm they can do to concrete, RAC having chloride ions more than 0.6 lb per cubic yard of concrete of Portland cement, are not suggested to be used in any construction activity [15].

### 2.9.5 Soils and Filter Materials

Soils and clays, along with other undesired materials, are found in abundance in the demolished masonry. They are dangerous because once incorporated in the material, are hard to remove later on, and negatively affects the durability of the final project. The only way to remove these organic soils and clays is conventional washing and sieving of the material, but it makes the process costly and time consuming. It is therefore suggested not to use materials with excessive amounts of clays and soils.

Percentage amount of undesirable materials should not exceed the values shown below [11]:

Wood – 0.1% maximum

Metals – 0.1% maximum

Plaster and gypsum board – 0.1% maximum

Depending upon the engineer's experience, location, and climate, such that they do not impact the performance of the designed and desired structure, these values can be adjusted.

### 2.9.6 Glass

In the recent construction designs, the use of glass is increasing by enormous amounts and since glass has the same density as that of concrete, it is easily incorporated into the demolished debris and masonry during demolition, which makes removal difficult. Another drawback of glass is that it may take an active part in alkali-silica reaction as well. Though a concrete and glass mixture is harmful, there are no values for glass contamination limits in concrete.[39]

Deleterious substances that could be find in recycled aggregate, their limited values and if get in excess, their effect on concrete are summarized in Table 6.

Table 6: Deleterious Substances in Recycled Aggregate

| Substance | Limited quantity | Effect on concrete |
|---|---|---|
| Bitumen | 5% | Reduction strength |
| Mortar & brick | 5% | Reduction in strength |
| Organic matters | Not specified | Reduction in strength |
| Chlorides & sulfates | Not specified | Deterioration when get hardened |
| Wood, metal, plaster & gypsum | 0.1% | Effect on properties of concrete |
| Glass | Not specified | Tendency towards ASR |

## 2.10 Precautions

Like all other materials, quality control and assurance are required when induction of recycled aggregate is desired in Portland cement concretes. If quality is not ensured the deleterious materials, possible in recycled aggregate, might adversely affect the quality of the concrete [15].

- Keeping in view the dynamic status of the construction industry, one cannot proceed without technical testing and proofs of any material. Same are required for recycled aggregate. At current, based on the research status carried out in the United States, RAC is limited to be used for concrete pavements, cement treated base courses, sidewalks, median barriers, curbing, and other non-structural applications unless alternative applications are approved by the specifying jurisdictions [15]. Precautions are therefore needed to be taken while testing this aggregate practically in projects.

- Being a recycled material, various state and local jurisdictional laws and regulations may be applicable for crushed aggregate. It is therefore important while working with recycled aggregate to contact state and local environmental and other local regulators to determine what other procedures are required before starting work.
- Undesired substances in aggregates can adversely affect concrete setting time, strength, and also cause expansive reactions that could result in the premature deterioration of the concrete and final product. It is therefore suggested that strict quality control and quality assurance procedures are carried out to ensure good use of RAC in the project instead of causing more problems and creating a costly, weak, and un-engineered project.
- Because of the fact that RAC may posses air entrained concrete mortar, it may be highly absorptive and can show low and highly variable specific gravity values. This can adversely affect the weighing and batching processes in the early stages of concrete production operations, which will ultimately affect the final design. Several trial batches are suggested before finalizing the last design because of this.
- RAC may yield higher than expected soundness values when subjected to conventional sulfate soundness testing methods. These testing methods may not be reliable for RAC soundness testing. Alternative methods should be sought out if the tests reveal unexpected results.
- Engineers are cautioned to check the recycled aggregates before incorporating them in the concrete if it is free from irrelevant solid waste or hazardous materials. If not available, methods and criteria for examining and approving RAC before using it should be established by local responsible and related authorities.

- Recycled aggregate to be used, shall meet the flat and elongated particles requirements of the specifying jurisdiction.
- Recycled aggregate shall be saturated with water for a time period that is sufficient to saturate all particles, prior to introducing it into Portland cement concrete mix, by means of water sprinkling systems or any other approved methods.
- At a time of batching, recycled aggregate shall contain water in excess of the saturated surface dry condition. Provision shall also be made for the free drainage of excess water.
- One of the approaches to remove or aside the deleterious and other unacceptable substances is stockpiling the recycled aggregates. It will also be helpful to judge the uniformity of the aggregate on site.

## 2.11 Recycling Equipment/Crushing Plants

Recycling equipment configuration affects product mix and plant efficiency as well. Also depending upon the site conditions, selection of equipment is influenced by the decision of whether to use a fixed crushing plant or a mobile unit. It is also important that mobile plants meet roadway restrictions to be allowed to move from site to site. One of the reasons to prefer mobile units is that fixed recycling site equipments can be more durable and larger in size but trading off lower unit production costs with reduced transportation costs for the mobile units.[9]

Smaller processing plants are a great concept and work well for asphalt recycling. For concrete, however, the preparation costs are enormous when using small crushers, because the materials need to be broken up to a smaller size and, hence, need much crushing. If only flat work or road work is being processed, it can be done but if the bridges, parapets, demolition debris, or building columns are being processed, then the large crushers are required. Another point of anxious is the wear costs which are also high.

Though mobile units are suggested to be preferred, but selection of a crushing plant depends on several factors, such as the availability of energy sources, labor power (though not much skilled labor is required), site conditions, type of material to be processed, the type of construction, and where this material was and is to be used. So, depending upon the cost-effectiveness, sometimes it is more feasible to use fixed units.

Simple processing plants for recycled aggregates are comprised of the following processes [4, 6]:

- A vibrating feed hopper and grizzly for arranging the hard portions from the inert demolished materials suitable for succeeding recycling.
- A jaw (primary) crusher for reducing the sorted materials to sizes up to 200 mm or smaller which can subsequently be handled by secondary or main crushers.
- Separators, manual hazard materials picking gallery and air separator for removal of impurities section before the materials are fed into secondary crushers.
- Cone (secondary) crushers for processing the clean materials into desired sizes of up to 40 mm or smaller.
- Vibratory screens (primary and secondary) for further classifying the crushed recycled aggregates into different sizes.
- Storage compartments for storing recycled aggregates when they are processed.

The generalized system, which is adopted by most of recyclers, is shown in Figure 5.

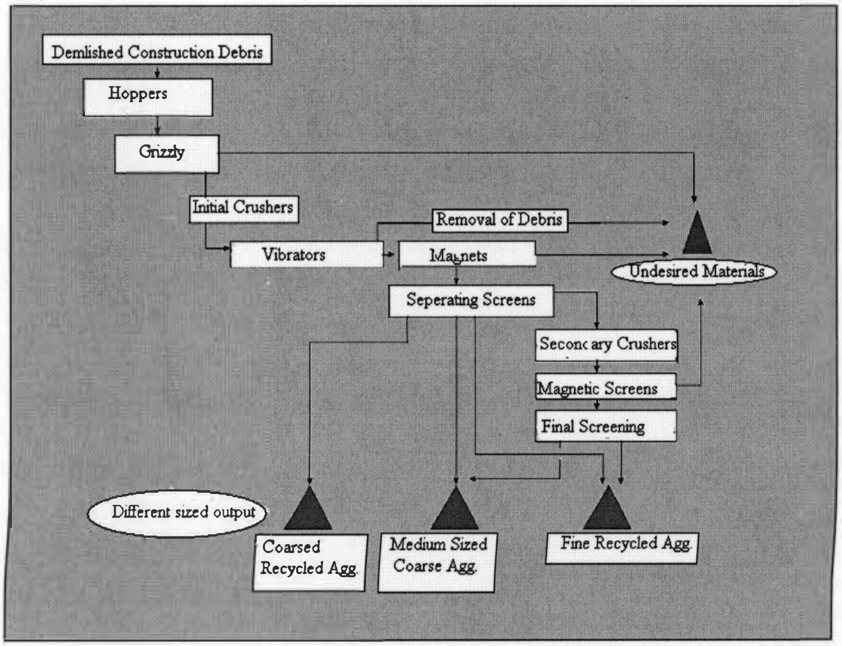



Figure 5: Generalized Flow Diagram for the Aggregate Recycling Operation[9]

The crushing plants for recycled and natural aggregates, currently in use are shown in Figures 6 and Figure 7.

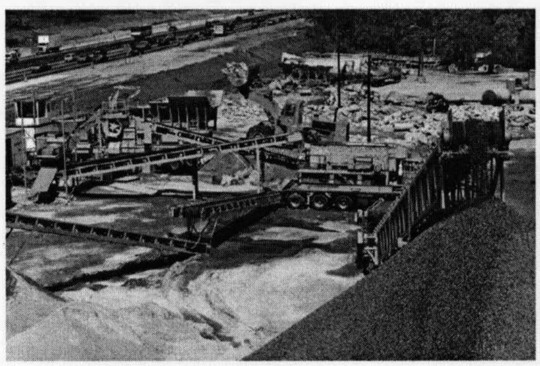


Figure 6: Recycled Aggregate Plant [9] Figure 7: Virgin Aggregate Plant [9]

## 2.12 Global Research

Concrete is one of the most important construction materials in use. This is apparent from the fact that approximately one ton of concrete is used per capita per year throughout the world [32]. This large dependence on concrete is an economic justification to seek improvements and new applications for a material that has been and continue to be the backbone of major construction works.

Recycling of concrete is a new concept compared to the recycling of steel scrap, paper, plastics, glass, or other common materials [55]. It will therefore take time to get established. Results have however shown that standard recycled aggregates can be produced with modified commercial plants that are used for producing crushed rock aggregates. Clearly this information could encourage clients and demolition contractors to direct construction and demolition waste for production of RAC, rather than disposing it to the landfill sites.[53] It further strengthens its application when it is claimed that 30% coarse recycled aggregate can be used, without any modification in the mix design, in concrete construction, and with performance similar to virgin coarse aggregates in concrete.[32] But still fear about the performance and difficulties of producing concrete with recycled aggregate, which has more potentials of variable performance, still daunts many potential producers and users. But it is expected and widely accepted that the demolition projects and technical guidelines will provide evidence for the necessary confidence for this material to strengthen its position and importance [9]. But still the key engineering and durability properties of concrete with recycled aggregate are found to be similar to corresponding virgin aggregates concrete, providing the mixes are of equivalent strength, achieved through respective adjustment in w/c ratio [55].

Seeing several potentials in recycling of aggregate, like cost-effective, environmental friendly, and easy to carry out, research on this material is on rise throughout the world. Due to these qualities, recycling of concrete is expanding in most of the developed and developing countries worldwide including the United States and

Canada. As an encouragement for its use, there are no regulatory or legal barriers to the use of recycled aggregates in new concrete pavements. Even the Federal Highway Administration and the US Army Corps of Engineers have encouraged the use of RAC in their projects [36]. But still the present status for RAC is "downcycling"[36] in most of the areas, where RAC is used in low-valued construction applications. Its use in structural applications in some European countries and Australia is making trends for its further and enhanced applications in other construction applications.

Due to the problems of land filling of demolished debris, collection and sorting of construction debris is becoming a standard practice required by many states and municipalities. Furthermore, for reuse of the demolished materials in Europe, Canada, and Japan concrete recycling is regulated and loftily mandated. In particular, Germany promulgated the national standards for aggregates in concrete and mortar to be used as guidelines for recycled concrete contents. German researchers have also demonstrated that recycled aggregates do not affect most important performances of concrete.

In Canada, the C-2000 Green Building Standards aim at making recyclable up to 75% of the existing structures. In Japan, the draft standard for use of recycled concrete was published in 1977.[14]

Usage of RAC exists in the Sydney Olympics buildings and Sydney casino in Australia, in foundations and walls in two big construction projects in Germany, in several demonstration projects in Norway, currently in the Twin Towers 7 projects in New York, strong support from Hong Kong, Japan, Turkey, Netherlands, and Venezuela tells the future prospects of this new material.

The growing trends of using RAC and some of the pioneer examples, found in research, [16] predicts its bright future:

- In 1990, Mr. Mellehorn reported that crushed concrete had relatively low compacted densities when compared to limestone, but has a high consistent density. He concluded from his research that RAC met all the United Kingdom specifications for type I granular base materials and should be considered as suitable granular subbase material.
- After experiencing problems in 1993, the existing pavements at the Orlando International Airport were removed and crushed again on-site into 3/4" maximum size aggregate. Tests were performed to determine the suitability of the recycled aggregate as a base coarse for taxiways in international airports. Tests resulted positive and also showed that RAC met all the required specifications of FAA P 209 for coarse aggregate bases; but, it was not used due to some problems in the contract documents and could only be used in shoulder pavements.
- In 1994, samples from commercial producers' stockpile of recycled aggregate were taken on a monthly basis in Australia for six months and were tested for grading, plasticity, compaction, and Los Angeles Abrasion loss. All the samples passed the required specifications for roads to be used in Australia.

Almost all the European Union countries are conducting research on RAC. Germany, Denmark, and Netherlands have done large amounts of research as compared to other European countries. The recent growing trends and latest laboratory and field tests by some researchers in Norway show how other countries are working and competing in this regard.

Waste arising from construction and demolition constitutes one of the largest waste streams within EU and many other developed countries. For example, it is estimated that core C&D waste (described as those types of materials that are obtained from demolished buildings or civil engineering infrastructures) amounts to around 180 million tons per year or 480 kg/capita/person/year in the EU. This ranges from over 700 kg/capita/yr in Germany to fewer than 200 in Sweden, Greece, and Ireland [53].

The average waste volume per capita in 1996 in the member countries of the EU has been estimated to range from 140 kg per capita in Sweden to as much as 6750 kg per capita in Luxembourg [52]. Point of interest is that with rise in the amount of demolishing, there is rise in recycling too and at present the level of recycling and reusing of concrete in EU is estimated to be about 25% [53].

One of the reasons that the idea of treating or tackling of the demolished debris and wastes in Europe is getting attentions is that most of the countries here have limited spaces and they can not afford the creation of some extra land for wastes. Apart from that here the countries like to compete each other, for instance, if Germany is trying to do some extra work on new technology, Norway and Netherlands will do some efforts in the some area. Another factor which can be considered also is that most of the European countries are in the favor of same conditions through out the Europe. It does not matter if it is related to economy, environment or another area.

Building and construction waste in the member countries of the EU is shown in Table 7 [53].

Table 7: Waste Production in Europe

| Country | Building waste in million tons | Kg/capita/year |
|---|---|---|
| Belgium | 7.5 to 8.0 | 70 to 800 |
| Denmark | 2.3 to 5.0 | 460 to 1000 |
| Finland | 1.6 | 320 |
| France | 20 to 25 | 340 to 450 |
| Netherlands | 13 to 14 | 870 to 930 |
| Ireland | 2.5 | 710 |
| Italy | 35 to 40 | 600 to 930 |
| Luxembourg | 2.7 | 6750 |
| Spain | 11 to 22 | 280 to 560 |
| Great Britain | 50 to 70 | 880 to 1220 |
| Sweden | 1.2 | 140 |
| Austria | 52 to 120 | 840 to 1900 |
| Germany | 22 | 2860 |
| Total | 221 to 334 | 607 to 918 |

### 2.12.1 United Kingdom

A thorough research on reusing the huge amount of material obtained from civil engineering infrastructures during their renovation or demolition was noted in the United Kingdom. One of the reasons was the steady rise in the national demand for aggregates since the Second World War. This demand was chiefly influenced by the sudden increase in the construction and house building markets, as well as government policies on roads and buildings. Researches also indicated that only this part of Europe-UK has enough gravel to serve the whole market in the next decade. But if the demand increases at current rate, supplies are expected to run short within about the next 20 years unless new aggregate sources are sought out. Recycled of used aggregates can however fill this space between supply and demand if it is considered. In order to find any other secondary material, the government must act now to encourage its use by restricting the supply of the current in-scene aggregates [39].

The estimates of aggregates for the UK are 30 million tons/yr and just over 500 kg/person/yr respectively, placing the UK second in use, after Germany. Moreover, Britain's building industry is a major extractor of raw materials and annually produces over 14 million tons of waste in the region of London alone [53].

RAC is better in some areas, therefore fewer restrictions on its use in the newly developed UK and EU standards and specifications are applied, like that given in BS 8500-2: Concrete- Complimentary British Standard to BS EN 206-2 Part 2: Specification for constituent materials and concrete. The approach to recycled aggregate adopted by the British Standard Institute in BS 8500-2 is to cover the coarse materials only and allow their use under enough exposure classes to ensure that there are no technical barriers to the use of such materials [53]. Furthermore, until more research is completed, usage of RAC is limited to foundations, paving, and reinforced or pre-stressed concrete in mild and moderate environment applications.

Outcomes of recent research in the UK are listed below:

- Both reinforced and plain concrete can be crushed using primary and secondary crushing machines to make it useable again for construction practices with desired and acceptable quality. Acceptable quality means that recycled aggregate should be free from foreign materials like metals, wood, hardboard, plastics, and papers etc.
- Recycled aggregates are found to have lower density (4% to 8%) [14] and higher water absorption (about 2 to 6 times) [14] than virgin aggregate. It is therefore suggested that care should be taken to determine these quantities before their use in concrete production.
- Concrete mixes containing recycled aggregate up to 50% have less stability [14]. Such mixes were found to be harsh, less cohesive, and have increased bleeding while comparing the values with the same concrete by replacing aggregate with virgin concrete. However, it is also found that these problems can be overcome by using filler material.
- To see the impact of RAC content on the maintenance of air content in concrete with the progress of time, tests were carried out for up to 60 minutes following alternate mixing and standing for a period of 5 minutes to replicate transportation and handling conditions. The results indicate negligible differences in air loss between natural and recycled aggregate concretes, suggesting no particular effect of RAC characteristics or source [39].
- The results have shown that up to 30% coarse recycled aggregate has no effect on standard 100 mm concrete cube strength, but thereafter a gradual reduction can be expected with increasing recycled aggregate content [39].
- A very small difference was found in tests for flexural strength and modulus of elasticity in the relative performance of natural and recycled aggregates. However, the

ultimate shrinkage and creep tests were found to increase with recycled aggregate content in concrete mixes. This is due to the increased proportions of cement content in such concrete mixes as the w/c ratio of this mix was reduced by increasing cement content to achieve 28-day strength equivalent to corresponding virgin aggregate concrete [53].

- Up to 30% coarse recycled aggregate had no effect on initial surface absorption measured at 10 minutes (ISAT-10) and thereafter ISAT-10 increased with increment in recycled aggregate. The depths of carbonation measured at a test age of 20 weeks were attributed to a number of factors. Initially, the quantity of calcium hydroxide in RAC will increase with an increase in the attached cement paste content. Later on, in these mixes, cement content was increased to reduce the w/c ratio to achieve equal 28-day strength, and as a result, there will be an overall increase in alkalinity in concrete when it gets hardened later on [53].
- A negligible effect of RAC content was noted on abrasion resistance.

### 2.12.2 Germany

The German government published the National Standard (DIN 4226-1000 Aggregates for Concrete and Mortar, 2002) setting the guidelines for recycled aggregate concrete. It was based on the work carried out by German researchers who demonstrated that recycled aggregates do not affect most performance characteristics of concrete, although it causes an increase in drying shrinkage and creep and also reduce modulus of elasticity [36].

The development of national standards put Germany as one of the pioneers in using RAC in civil engineering infrastructures. Following these standards, established by the government, the first building constructed with RAC in Germany was "Vilbeler

Weg". The trend then started and recycled aggregate was used again in the second building, "Waldspirale", which was constructed in Darmstadt in 1998-99. Before using recycled aggregate in these projects, the results in different tests showed that it is of equal quality and strength as compared to concrete with natural aggregates.

One of the main concerns of RAC was the higher water absorption rate which could lead to lower dry density. In order to control that, in rainy seasons the aggregate was kept moist and fully saturated. It was also found that during warmer days the aggregate absorbs much of the water in the first 10 to 15 minutes which results in faster development of rigidity. The problem was solved by providing continuous sprinkling water. In order to compensate for the consistency loss, the cement paste was increased because of the rough surface of recycled aggregates. These two modifications to the conventional process helped to achieve the same results as natural aggregates while using recycled aggregates [18]. After applying these two alterations in the production process, concrete with recycled aggregate showed no relevant difference to concrete made from natural dense aggregate and was cast or pumped just like any other standard concrete mixture. Another advantage of sprinkling water or dumping recycled aggregate in water is that it will help in removing the powdery material.

Work done for reuse of recycled aggregate in Germany is discussed as:

- In 1996, a new law, "Circulating Economy and Waste Material Law" was introduced in Germany. According to this law, any person who produces, sells, or consumes a product has to later recycle or dispose off the remaining waste material in respectful to the environment. It was in the process to make the concerned people think about recycling it.

- The research project "Building Material Cycle in Structural Engineering" led to a new construction guideline called, "Concrete with Recycled Concrete Aggregate" which was recommended and published by the German Committee for Reinforced Concrete.
- On February 20, 1998 the new construction guideline, "Concrete with Recycled Aggregate" was presented to the construction professionals. Therefore, one and a half years after the German law, "Circulating Economy and Waste Material Law" saw a legal status when it was passed. It also consists of a guideline for the engineers, who are conscious of the environment.
- A test research was carried out for three mixtures. The main difference of the three mixtures is the percentages amount of recycled aggregates:
  - RC-N: Normal concrete with 100% natural aggregate
  - RC-A: This concrete consists of both natural and recycled aggregates
  - RC-B: The coarse aggregate in this mixture is entirely recycled aggregate

  Properties found for different parameters are listed in Table 8 [29].

Table 8: Properties of Specimen

| Concrete properties | RC-N | RC-A | RC-B |
|---|---|---|---|
| Density | 2400 kg/m$^3$ | 2280 kg/m$^3$ | 2140 kg/m$^3$ |
| Air space ratio | 1.1% | 3.0% | 2.5% |
| Slump (after 10 min) | 0.47 m | 0.44 m | 0.40 m |
| Compacting Factor | 1.04 | 1.09 | 1.07 |
| Cube strength | 47 N/mm$^2$ | 44 N/mm$^2$ | 31 N/mm$^2$ |
| Cleavage Strength | 3.7 N/mm$^2$ | 3.2 N/mm$^2$ | 2.4 N/mm$^2$ |
| Modulus of Elasticity | 33.000 N/mm$^2$ | 25.100 N/mm$^2$ | 21.000 N/mm$^2$ |

Different cubes with varied dimensions were produced. The standard dimension of 150x150x150 was used for all of them. Production of 25 cylinders with a diameter 150 mm and a height of 300 mm for the creep and shrinkage tests were also part of the work. Tests proved that recycled aggregate has high tendency of creep and shrinkage [30].

Some cylinders from each series were sealed to reduce the influence of shrinkage on the concrete deformation. After 28 days curing, they were loaded into the compression machine and increasing stress from 30% to 70% was applied. The test shown lower values of strengths and higher of shrinkage and creep compared to 100% virgin aggregate concrete, but they were still under the desired values [30]. Different stages of load applications on specimens are shown in Figure 8.

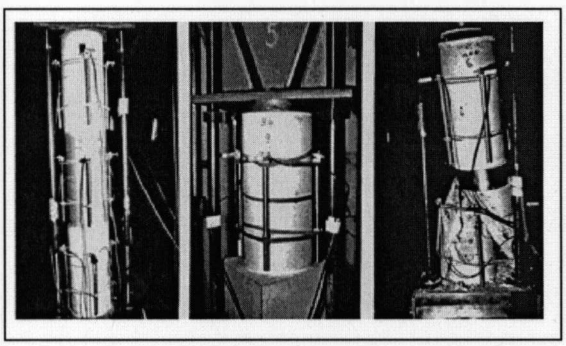


Figure 8: Specimen Under Increasing Load Till Failure [30]

The results shown with the application of 70% stress made the use of recycled aggregate in concrete doubtful. After 10 days of 80% stress application the cylinders were found scaled in the laboratory.

- The building project, "Vilbeler Weg", was an office building with parking area erected. For demonstration purposes, a complete section of this building was constructed from concrete made with recycled aggregate derived from concrete rubble. The aim of this project was to demonstrate the general applicability of the current research results and to define the basics of the practical quality management system. It was decided that in the production of concrete for indoor and outdoor components, only recycled aggregates will be used. The construction still exists after the successful completion and is in use till date. Engineering maps, designed by German engineers for Vilbeler Weg project are shown in Figure 9.

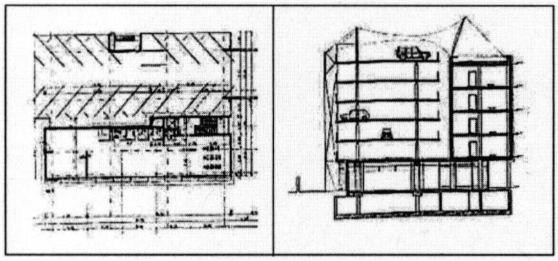


Figure 9: Engineering Maps of Vilbeler Weg Project [29]

- The first construction member of concrete with recycled aggregate in the ground floor's ceilings was constructed on November 11, 1997. Concrete construction ended in mid February 1998. The total quantity of concrete with recycled aggregate used was estimated to be 480 cubic meters. The concrete had a maximum grain size of 16 mm.
- The demonstration project of "Vilbeler Weg" proved that the application of the presented production concept is possible, if it is combined with an appropriate quality management system. To ensure, a concrete having the same quality as that of concrete made from virgin aggregate, certain parameters and boundaries have to be considered:
    - As the water absorption of the aggregate in use was low due to its high density, the workability could always be restored by adding super plasticizers. This would not be possible if the aggregate in use had a lower dry density and therefore higher water absorption
    - The variation of actual water/cement ratio in the concrete mix led to a deviation of compressive strength results. As in the case of workability, an aggregate with greater

water absorption would make it necessary to consider the core moisture in the dosage of aggregate and water to guarantee a constant actual water/cement ratio and ensure that the standard deviation of compressive strength remains within the reasonable parameters.

o Because of different water absorption values, the volume and mix proportion of the produced concrete was also noted to be varied. This fact continues throughout the production phase and was considered in the dosage of concrete mix proportions, so that the quantity of concrete ordered at the construction site is guaranteed.

- In the construction of one of the buildings, the amount of water added in the concrete was kept constant which resulted in a variable workability due to changing weather conditions, unsheltered storage of aggregate fractions, different aggregate surface, and core moisture. It was then suggested either to mix all concrete the same day or search ways to keep temperature constant every time when mix is desired.
- The contractor asked for the concrete with a stiffer consistency during construction of the "Vilbeler Weg" project. As a result, super plasticizers were added before mixing concrete. The reason was to minimize the hydration temperature by limiting the amount of cement paste and to gain workability.
- The latest draft of the German guidelines, "Concrete with Recycled Aggregate" allowed substituting up to 33% of total natural aggregate with recycled aggregate by volume. This is the suggested proportion of recycled aggregate if no changes are desired, comparing to normal concrete.
- Research proved that measurement of the water absorption beyond 24 hours showed no remarkable change in value; therefore, the 24-hour water absorption value can be

defined as the aggregate maximum water absorption value. This behavior is typical for aggregate derived from concrete rubble.

### 2.12.3 Norway

Norway currently lags behind many other European countries in the field of recycling demolished buildings and construction materials. However, many promising deconstruction initiatives indicate that the general awareness about deconstruction related issues is increasing and that more use and recycling will take place in the near future. Research also indicates that there is a growing trend in interest for deconstruction related issues in Norway.

Waste handling is attracting increasing attention and several practical initiatives are taken by trade and the authorities to encourage recycling of building and construction waste in Norway. With keen interest by Norwegian engineers, several pilot projects on reuse and recycling are also being undertaken in Norway. Seeing the growing trend in this market, it can be guessed that Norway will soon be one of the countries with the same status as Germany and the process of intense research on recycling aggregate and its use in infrastructure will start soon.

Though the reduction of construction and demolition waste through recycling and reuse has received increased attention in the recent years, yet it is still not a standard practice in Norway. The main reason for this late start is the abundance of natural aggregates, easy availability, and its low price throughout Norway; yet, the environmental concerns, reduction in dumping areas, and competition with other European countries in this area are some of the factors which made Norwegian government take some initiatives [52].

Changes in the Norwegian building and construction industry in the last few years lean toward more recycling and reuse, utilizing the C&D waste for new construction while following and conducting the general trend on the rise in many countries around the world [23].

Annual C&D waste production in the country is approximately 1.5 million tons of building waste from the construction, renovation, and dismantling of buildings with about 70% (1.1 million tons) consisting of concrete and rubble masonry and about 22 million tons from the construction of bridges, ports, roads, railroads, airports, etc. This is low compared to most of the other European countries. Rough estimates indicate current levels of recycling and reuse in Norway to be 10% to 20% [23]. For the Oslo region, it has been estimated that between 25% and 50% of the waste is recycled or reused, while the corresponding share is estimated to be close to zero for the rest of the country [52].

*Encouragement by the state and industry professionals*

Due to the growing trend among the general public and strong lobbying by the environmental organizations, environmental awareness in the building and construction industry is also increasing. Apart from the state, several initiatives have also been taken by the industry professionals and trade unions. On part of state, the Norwegian government is applying new rules through different ways in order to encourage the reuse of demolished materials in further construction.

Some of the examples found in a literature search are listed below:

- The Norwegian Concrete Association has developed national guidelines for classification of the use of recycled aggregate in the production of new concrete. After research, tests and depending on the classification of the aggregate and the quality of the concrete, up to 30% by weight of recycled aggregate is allowed [52].

- The pollution law from 1981 is one of the important laws regulating the handling of building waste. This law is based on two principles; the first one is that waste should be handled in a way that minimizes damage and inconvenience, and recycled where there is environmental benefit, resource efficiency, and is economically acceptable. The second principle is that the polluters should pay the full costs of the environmental damage they are causing. According to the law, building and construction waste is defined as production waste and the same requirements therefore apply as for other types of waste.
- There are local charges for delivering waste on disposal sites. These charges are levied to cover the full cost of establishing and running sites. The taxes may therefore be charged variably between the different local councils in the country.
- A national tax on depositing was enforced in 1999. The tax is 300 NOK (US $ 35) per ton of organic or unsorted waste. If the waste is incinerated, a basic tax of 75 NOK (US $ 9) per ton and a supplementary tax of 225 NOK (US $ 26) per ton also apply [51].
- NORSAS is a national competence centre for waste and recycling. It is responsible to promote waste reductions, increase recycling, safe handling, and final treatment of the waste. It shall also collect, treat, and disseminate information and knowledge about waste handling.
- Eco-Building is an initiative from the building and real property trade to contribute to environmental improvements and achievements of national environmental goals. It is about a US $ 7 million project, financed by the Ministry of Environment, the Ministry of Trade and the Industry and Ministry of Petroleum and Energy. The goal of the

organization is to reduce the building and construction waste by more than 70% by establishing a commercial market system for waste recycling [51].

- Two trade organizations, BNL and TELFO, are developing a national action plan for building and construction waste. In the first phase of this project, a state of the art report on building and construction waste was completed in December 1999. In the second phase, certain goals for waste reduction and recycling are planned to be established together with measures to reach these goals. This work is partly financed by Eco-Building.

- Recycled aggregate in building and construction (RESIBA) is a three year research project carried out by a number of manufacturers, enterprises, and organizations in the Norwegian building and construction trade. The goal of RESIBA is to make recycled aggregate a competitive product and to bring Norway up to the same level as rest of the European countries in this work.

RESIBA consists of three sub-projects. The first sub-project is titled "Declaration and Quality Control". The aim of this project is to provide basic information about the most important technical properties of recycled products and estimate possible environmental problems related to it. The project is linked to the European research program, "Use of Recycled Aggregate in the Construction Industry".

The aim of the second sub-project, "Demonstration Projects", is to evaluate the use of recycled aggregate in full scale construction and initiate pilot projects.

The third sub-project, "Information Dissemination" is aimed to spread knowledge and results from the project to the building and construction trade, as well as to the politicians and authorities.

*Demonstration/Pilot Projects*

After searching the area for potential benefits and development of several projects, some demonstration or pilot projects have been carried out in Norway by Norwegian engineers and state professionals to test the feasibility and expected benefits from this new aggregate when used in concrete.

Some of the projects found in a literature search are listed below:

1. One interesting pilot project that already has been carried out is the use of recycled aggregate in sprayed concrete. The sprayed concrete was used to cover EPS insulation used in the foundation of a tramcar line in Oslo. The project is claimed to be the first one in the world where recycled aggregate has been used in sprayed concrete (without recycled aggregate, with 7%, 14% and 20% recycled aggregate [23]). The project showed promising results with regard to mixing, spraying, and the mechanical properties of the concrete.
2. A new state hospital was constructed just outside Oslo in July 2000. The old State Hospital is located in the middle of Oslo. A project called "Pilestredet Park" has been established to convert the old hospital area into a small town with about 900 apartments, the Oslo University College with its 3000 students, a number of offices and shopping malls.

The old hospital was owned by the state, but most of the site has now been sold to private sectors. The contracts include strict requirements with regard to reuse and recycling of the demolition materials. It was decided by the authorities to utilize almost 90% of the total expected waste of 85,000 tons in the whole process with the allowance of only 10% to be deposited. The waste from digging works is estimated to be between

300,000 and 400,000 tons. Since the project area is located in the middle of the city, it is aimed at reducing the transport of waste as much as possible. Most of the material will therefore be recycled on the site. A large number of the demolished concrete and brick waste will be used as aggregate in new concrete.

3. In August 2000 the Oslo Public Roads Administration opened a new motorway through the Svartdal tunnel. A 50m test section was established outside of the tunnel using approximately 600 tons of RAC as subbase. In addition, a 50 m adjacent section was established using natural aggregates in subbase layer for reference. Plate loading tests were performed to measure the modulus of elasticity of the two sections. In addition, the two test sections are currently being monitored measuring rut depth and longitudinal evenness of the road surface.
4. A new tramline in Oslo was completed in 1999, including the use of approximately 4000 cubic meters of RAC as base material on top of a lightweight filling and backfill behind retaining walls. The project has been monitored by RESIBA who have been measuring deformation of the RAC base layer.
5. RAC has also been used successfully in Oslo for a bus parking lot, pedestrian/cycle paths, and as backfill in drainage trenches in 1997.
6. Full scale laboratory testing conducted by Norwegian Building Research Institute (NBI) indicated that RAC would function well as backfill materials in the pipe zone in utility trenches.

In a demonstration project, the municipality used about 1000 tons of recycled aggregate as backfill in a 600 m utility trench for water and gas drainage from a landfill.

Use of recycled aggregate in different demonstration projects is shown in Figures 10 and 11.

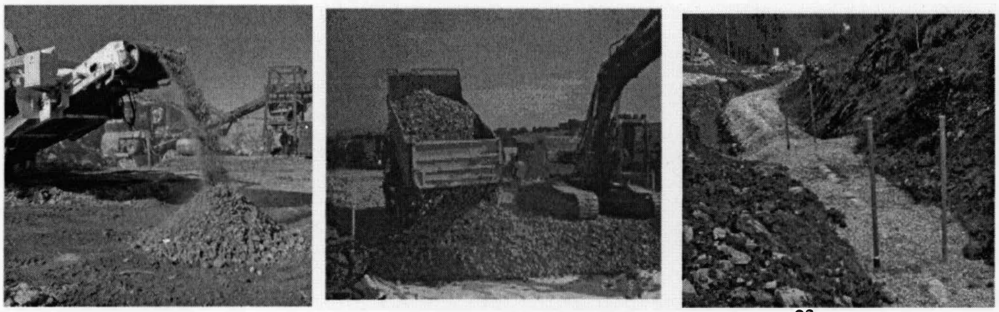


Figure 10: Usage of RAC in Different Projects [23]

- During the construction of a new parking garage outside Oslo, the contractor used recycled aggregate by 20%, substituting it over natural aggregate in coarse form and used it in foundation. Concrete production and casting of the foundations were successful and the laboratory test results showed that the concrete met the material properties as specified. Laboratory testing of concrete using up to 100% RAC has also yielded positive results [23].

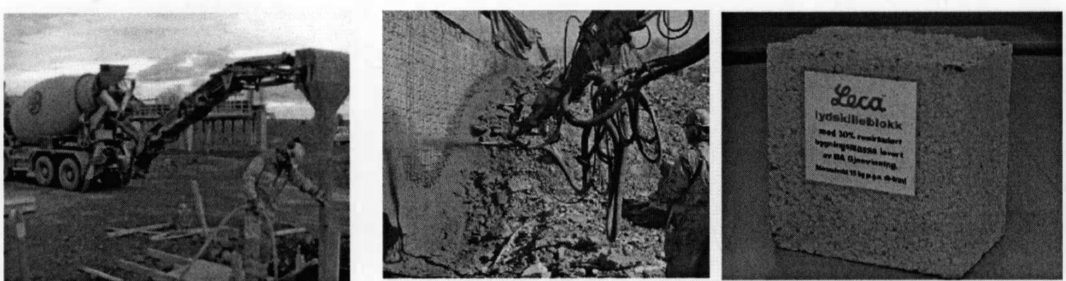



Figure 11: Different Proportions of RAC is Used in Several Projects in Norway [23]

- The production of Leca masonry sound insulation blocks using 30% RAC [23] is another milestone in the work related to recycled aggregate in Norway. Laboratory testing demonstrates that all specifications for the Leca masonry sound insulation blocks are met during this demonstration

- The construction of a school just outside Oslo is one of the demonstration projects initiated in Norway under the supervision of many organizations, mainly RESIBA. The area of this new school is about 13,000 $m^2$. Construction was started in the summer of 2001 and the school was almost completed for fall 2003. The high school building incorporates the use of RAC for unbound and bound applications, utilizing the results obtained through laboratory and field-testing in the RESIBA project.

In foundations and in half the basement walls and columns, 35% of the natural coarse aggregate was replaced by recycled coarse aggregate. A total of 800 $m^3$ concrete with RAC was used. The remainder of the basement was cast using 100% natural concrete aggregate. To avoid the risk of any future complications, concrete with recycled aggregate was not used for sections of the structure expected to be exposed to freeze-thaw action. Test results later showed however, that concrete with 35% coarse recycled aggregate had excellent freeze-thaw resistance [34].

Visually, the concrete with 35% recycled aggregate looks just as even colored as the concrete with 100% natural aggregate. The use of 35% recycled aggregate did not cause any noticeable increase in cracking or other constructional problems [34].

In general, the technical results from various laboratory tests and demonstration projects using RAC are overall positive. Material properties such as mechanical strength, density, and water absorption are significantly different compared to natural aggregates. However, important functional characteristics such as deformation stability, load distribution, and permeability are similar to those of natural aggregates. Laboratory testing of concrete replacing up to 100% of coarse aggregate with recycled aggregate also yielded positive results. Concrete with as much as 35% natural aggregate of the coarse aggregate replaced by recycled aggregate was successfully used in regular construction in Norway. None of the structures used as demonstration projects have suffered any kind of deterioration or damage due to use of RAC as an alternative to natural aggregates. For most of the demonstration projects, the use of RAC ended up reducing the costs compared to natural aggregates. This is, of course, due to the lower cost of about 50% less per cubic meter of RAC as compared to natural aggregates [34].

*Research on Leaching Effects of Using RAC*

Leaching is one of the main concerns with using RAC in construction. Different research, apparatuses and tests, are underway to investigate the effects of RAC on the water table when it is used in highways. The Norwegian government carried out several laboratory and field tests under their Research and Development program – RESIBA, to investigate this area of leaching. Achieved results from a field site study, which was focused on possible impacts from RAC on the soil system, verified significant influence, including increased soil-pH and increased amounts of calcium in the soil water.

In the field test a site was established in the soil deposit next to a utility trench. This trench contained an impervious pipeline with the intent to collect water from the road surface in a sedimentation basin. RAC was used as a backfill material in the pipe zone of the trench and RAC and local soil were separated by a permeable fiber membrane. The construction was finished in spring 1997 and the field site experiments were started in the spring of 2000.

Sampling of soil water was carried out by inserting four ceramic filters at sampling points R1, S1, S2, and S3. Points are shown in Figure 12.

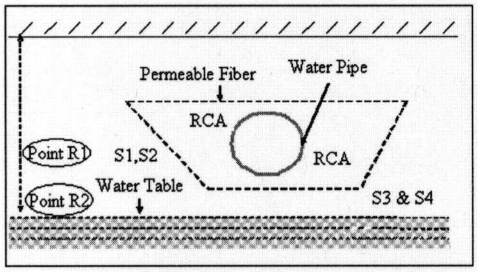



Figure 12: Samples and Reference Points Used in Experiments [51]

All sampling points are located in the unsaturated zone. These samples were taken in the spring of 2000 and the autumn of 2001. Atomic absorption spectrometry and inductively couplet plasma atomic emission spectrometry were used to determine the chemical analysis of the samples collected. The results showed the indication of some organic and inorganic materials in the samples. The materials found were, As (arsenic), Pb (lead), Cd (cadmium), Cu (copper), Hg (mercury), Ni (nickel), Zn (zinc), Ca (calcium), Mg (magnesium), PCB (polychlorinated biphenyls), and PAH (polycyclic aromatic hydrocarbons) . Due to the alkaline nature of the test materials and the absence of buffering capacity in de-mineralized water, a large increase in the pH of the samples was expected. The results proved them. Consequently, the extent of increasing pH can be related to the leached amount of Ca [51].

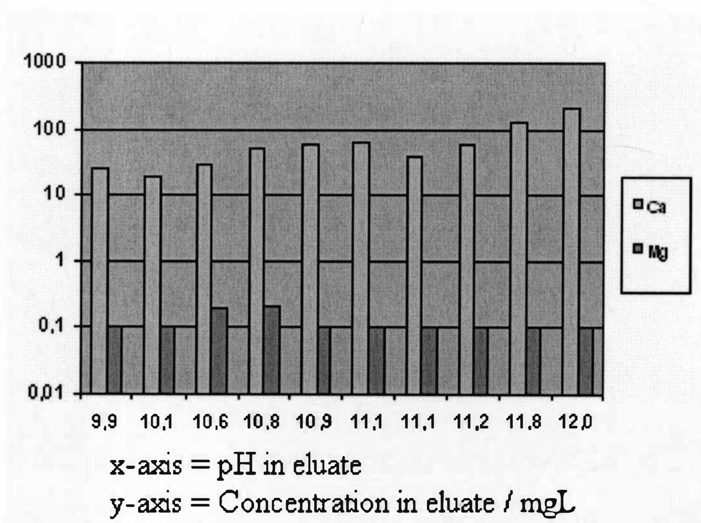



Figure 13: Values of Ca and Mg from Laboratory Tests [51]

No influence from RAC on soil with respect to metals, PCB and PAH, was found at the site. The only influence on soil from RAC was the release of calcium and consequently an increase in soil pH, which was not considered to be a negative point [51].

### 2.12.4 Japan

After a terrible disaster in 1945, it is a great success that Japan managed to be in its present developed form. With all other technological advancement, the construction industry and civil engineering infrastructures of Japan also made a remarkable progress. Infrastructural advancement can be judged by the amount of cement used in Japan since then. Research has shown a record usage of cement by the Japanese construction industry since 1945.

In 1997, the Japanese cement industry accepted 27 million tons of by-products. Regarding the blast furnace slag, 12 million tons (55%) out of the total product of 22 million tons was used; regarding fly-ash, 2.73 million tons (53%) out of the total product of 5.13 million tons was used. In 2000, 2.64 million tons of gypsum, 1.91 million tons of sludge, 1.5 million tons of slag from metal refining other than steel and 0.8 million tons of converter slag were used [1].

Japan has adopted a more standardized, modified, and specific approach towards recycling. The federal regulations require the maximum recycling of useful resources, including demolishing of used concrete. Therefore, structural concrete is classified according to its recycling ability. This classification includes separate classes for concrete that can be recycled with or without minimum improvement. According to this concept, concrete can be designed before it is placed so that its debris would be used as concrete materials after it has been demolished. This concept is termed “Completely Recycled

Concrete (CRC)" which is defined as concrete whose binders, additives, and aggregates are all made of cementitious materials, and all of these materials can be used as raw materials of cement or recyclable aggregates. When conventional concrete is replaced with CRC, the problems of concrete waste generation and $Co_2$ emission are reduced remarkably [36].

Japan has a history of more than quarter of a century of research on recycling demolished concrete for useable concrete, yet relatively little concrete has been recycled in the country. One of the reasons in this low pace is the price of ordinary Portland cement that has not risen for the last 30 years in Japan, plus the quality has remained as high as it was before. The increase in the cost of aggregate has been less than that in general consumer prices because of efficient mass-production. Another main reason which is preventing greater use of recycled concrete is that almost all concrete is supplied as JIS A 5308 ready-mixed concrete and that concrete other than JIS A 5308 is not easily accepted. The JIS Civil Engineering Committee made a recommendation in 1998 to establish new JIS standards to enhance and encourage the use of recycled materials in construction industry, which resulted in the formation of a committee for establishing a new JIS push for recycled materials under the supervision of Japan Concrete Institute (JCI). The committee presented two drafts in 1998 and 1999 respectively. One of which was published as a JIS Technical Report, TR A 0006 "Recycled Concrete Aggregate" in 2000 [01].

In 1991, the Japanese government established the recycling law, which required relevant ministries to approve materials that they must control, and to encourage the reuse and recycling of those materials under their responsibility. The Ministry of Construction

(MOC) nominated demolished concrete, soil, asphalt, concrete, and wood as construction bi-products. MOC also presented the "Recycle 21" program in 1992, which specifies numerical targets for recycling of several kinds of construction bi-products. The target for the recycling ration of demolished concrete in the year 2000 was 90% and the actual results for 1990, 1993 and 1995 were 48%, 76% and 65%, respectively. In 2000, it reached 96%, but almost entirely as a subbase material for road pavement [01]. For further progress the Japanese government is still trying to make several laws and rules to encourage the recycling and reuse of many construction bi-products with emphasis on the recycling of aggregate. Several trials are now underway to enhance the use of demolished concrete for concrete.

The MOC implemented several action programs in order to encourage the usual practice and reuse of recycled aggregate. They issued some quality parameters for recycled aggregate listed in Table 9 [01].

Table 9: Quality for Recycled Aggregate (1994, MOC)

| Class | Absorption | Soundness |
|---|---|---|
| I | < 3% | <12% |
| II | < 3% and < 40%<br>Or<br>< 5% and< 12% | |
| III | < 7% | ------- |

The JCI committee started to draft a JIS/TR for recycling of concrete with the following policies:

- A new JIS is to be created for recycled concrete in whole, not only for recycled aggregate.
- Recycled concrete must be classed independently from JIS A 5308.
- Applicable areas in structures where recycled concrete can be used should be limited.
- In order to facilitate quality control, the number of classes of recycled concrete should be reduced in number.
- Quality control layout will be specified due to variation in concrete to be recycled.
- When skilled engineers use recycled concrete, they will explain and extend its scope application.

Some of the outlines of the JIS/TR are as follows:

- Report specifies, “Recycled Concrete”, which is made using recycled aggregate from demolished concrete of different structures.
- Recycled concrete is further subdivided into three classes:
  - “Normal” recycled concrete should be used for filling concrete and leveling, which are non-structural members where high strength and durability are not required.
  - “Chlorides Controlled” recycled concrete is to be used the same as normal concrete except for members with steel reinforcement.
  - “Flexible use” recycled concrete is to be used for a wider range of members, sometimes for structural use under the guidance of an expert or engineer who has expert knowledge of recycled concrete.

In Japan, research on the use of demolished concrete is progressing in several ways, some of them are [1]:

- Improving the present conventional methods of recycling demolished concrete and obtaining aggregate of good quality; for example, by improving the crushing machine.
- Establishing a perfect recycling system with the best results and zero waste.
- Extending the scope of use of recycling concrete; for example, by changing the mix proportion, mixing method, adding other materials, and so on.
- Establishing a more practical and economical system by "down-cycling."

*High quality recycled aggregate concrete through decompression and rapid release*

The higher water absorption of recycled aggregate requires extra water. This results in high workability and ultimately a lower inferior bond between the binding materials. The previous methods used to enhance the quality of the final products were to obtain a high quality recycled aggregate or use a high range water reducing agent and additives to improve the performance of cement paste in an aggregate of lower quality. Both alternatives ended up with a high cost, which obviously is not in favor of recycled aggregate, which is aimed to reduce cost and improve quality. To overcome such problems the Japanese civil engineers came up with a new idea of decompression and rapid release (DC-RR). A high quality recycled aggregate concrete can be obtained through a DC-RR procedure applied after normal mixing of concrete with recycled aggregate. Through this method of improvement, the quality of transition zone between aggregate and cement matrix can be improved astonishingly. The process is simple and the results are best. The pressure in the mixture is reduced during mixing (decompression) then, when the pressure reaches certain level, it is returned rapidly to atmospheric level (rapid release) to bond the aggregate and the paste [3].

It was found that using this method, compressive strength of recycled aggregate concrete can be increased by about 20%, creep and carbonation depth can be reduced by about 20% and 30% respectively [3]. This method does not have any significant changes on shrinkage or freeze-thaw for concrete.

### 2.12.5 Korea

- During several site and laboratory tests in Korea, it was reported that well-graded RAC may produce higher resilience modulus than the natural aggregates. For laboratory research the aggregate was obtained from a housing redevelopment site and a concrete pavement rehabilitation project. For tests, two different RAC (one was finer (A) than the other (B)). Results obtained are shown in Table 10 [41].

Table 10: Test Results with Different Proportions of Aggregates

| Property | RAC-A | RAC-B |
|---|---|---|
| Average Specific Gravity | 2.527 | 2.539 |
| Los Angeles Abrasion | 32.9% | 43.6% |
| Water Absorption | 1.43 to 6.77 | ----------- |

The visual inspection of RAC in this study revealed that the surface of the aggregate is rough but still it contains approximately 70% to 90% normal aggregate.

## 2.13 Recycled Aggregate Concrete in the United States

In the current market of any sector throughout the world, the value of an element is scaled by comparing it to its status and standards in the United States. Due to this fact, after searching growing trends of recycling of aggregates in world, the focus is its comparison with standards, work and status in the United States.

Like all other countries mentioned before, recycling of aggregate is on rise in United States too. It is getting the same boost and attentions as all other sectors are getting to conserve environment and natural resources. The reason, this sector of aggregate and its recycling is getting attention, is the rapid increase in different construction sectors. With this growth the amount of demolished concrete is anticipated to grow at the same rate as well that result in problems, with dumping in landfill sites as the only solution. The other alternative is to recycle this demolished material and make it useable again.

In 1991, the annual production of aggregates in the United States was calculated to be above $ 7.7 billion. It was confirmed to be the largest non-fuel mineral commodity produced. Half of this production was used in building industry while the rest was claimed to be used in other public health works [38]. This increasing trend of aggregates and cement can be estimated by the facts that they make up more than 80% of the total aggregate market, while the annual production rate of demolished debris is estimated to be 200 million tons, which is mainly because of increase in the rate of construction aggregates which increased from 36% in 1900 to 70% in 1958 [5]. With the increase in the production and consumption of concrete (10 billion tons/year of concrete produces worldwide, US contributes 500 million tons/year to this production [33]) and cement, the rate of production of demolished debris increases as well. This pace is estimated to be increased by 170% between 1994 and 1996 [9]. According to the annual report of UNHRP in 1994, the amount of construction wastes estimated in the United States was 150 million tons per year. Concrete contributes about 52% (78 million tons) of this waste. Only 42% (33 million tons) of the waste contributed by concrete gets recycled and 73% (24 million tons) of this recycled aggregate get used in low-value applications, such as fill and road base. While rest of 58% (45 million tons) of waste contributed by concrete only, go into landfills [33].

In another research study, the overall production of natural aggregates in the United States was estimated to be about 2.2 billion tons in 1996; the nation highway system used about 40% of this production [40].

Current research had shown that 50% aggregates, obtained from all cement concrete debris and 20% of all asphalt pavements are used as backfills. 85% of all the recycled aggregate is further used in roads, and 90% aggregates from asphalt pavements are reused in asphalt mixed concrete [9].

The construction and maintenance of highways plays an important part in the industrial development of a country. Once they are constructed it is also necessary to keep them in proper shape with regular maintenance and repair. In the United States more than 100 million tons of worn out asphalt pavements are recovered annually. Still, 15% to 20% of this amount goes to landfill sites while the remaining 80% to 85% is recycled. Two-thirds of this recycled aggregate is used as road base the remaining third is used as aggregates for new asphalts and hot mixes [5, 9].

According to an estimate prepared by Construction Materials Recycling Association, 100 million tons of concrete is recycled annually into useable form. This amount is 1% to 5% of the total aggregate demand in the United States, which is about 2 billion tons annually [5, 9]. In 1995, the recycled aggregates used were about 0.4% of the total aggregates consumed in the whole year [9]. In 1966, more than 2 billion tons of crushed stone, sand, and gravel were consumed in the United States, much of which was used in road construction [9]. The figures show that this available supply of recycled aggregates is small compared to the demand, though they meet the economical demands of the current market [9] because the rest of the 95% demand is still compensated by the natural resources of aggregate. In 1998, about 1.5 billion tons of natural aggregate from 3400 queries was crushed and used. 1.2 billion tons of this material was used in construction applications. 68% of the aggregate recycled was used in road bases for highways [5].

Though the precise statistics are not available, the estimated sources and their current market sector are shown in Figure 14 [9].

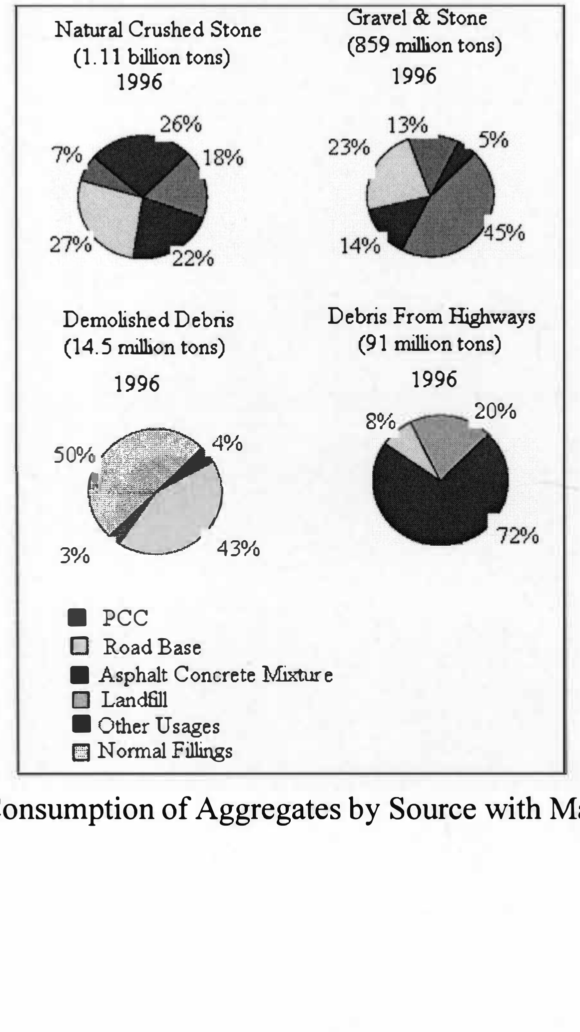



Figure 14: Consumption of Aggregates by Source with Market Sector [9]

2.13.1 Recent Research by the Federal Highway Agency (FHWA)

The FHWA is one of the biggest organizations in the national infrastructural development and is working to counteract the problems related to demolition materials from constructional work. At present one point of interest for FHWA is recycled aggregate. They are also working in close collaboration with AASHTO, EPAs, and the American Concrete Institute (ACI) to develop guidance information on how the states can use recycled aggregate in highway applications [20].

In one of their recent surveys by the pavement recycling team of FHWA, they worked to identify the current use of RAC with its benefits and to plan strategy to overcome hurdles. To pinpoint areas, past experience and the potential markets for RAC were chosen as the selection criterions. FHWA selected five state departments of transportation (SDOTs) throughout the country. They were from Virginia, Texas, California, Minnesota, and Michigan. The main goal was to identify the current state of RAC in these states and to spearhead the transfer of knowledge and experiences to other SDOTs. After surveying the current condition of RAC throughout the country, FHWA reported its different applications in all the states [20].

Current use of RAC in different construction applications in all the states were published in their recent study by FHWA after that research study. They are shown in Figures 15, 16, 17, 18 and 19 [20].

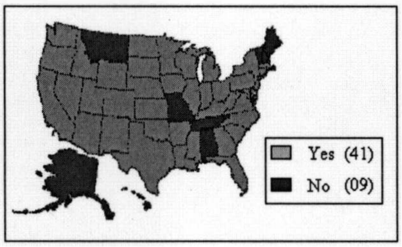


Figure 15: RAC as Coarse Aggregate

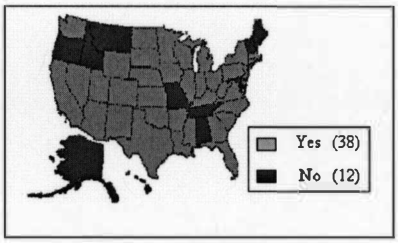


Figure 16: RAC as Base Aggregate

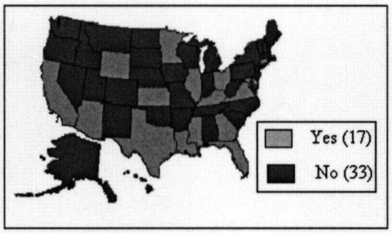



Figure 17: RAC in Different Applications

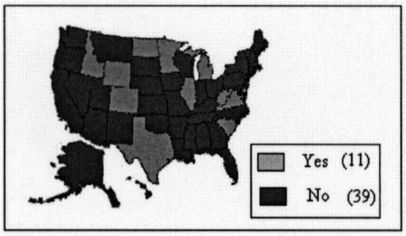



Figure 18: RAC as PCC Aggregate

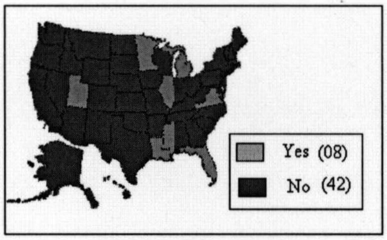



Figure 19: RAC as Hot Mix Asphalt Aggregate

Points of importance noted by different researchers about the US are described below:

- Desired results can be obtained only if the allowable amounts of impurities like sulfate, chlorides, and alkali-reactive aggregates are permitted while working with recycled aggregates.
- Aggregates obtained from demolished buildings or highways may contain certain amounts of deleterious substances which can affect the quality of the final product. It is therefore important to establish special quality control and assurance provisions to tackle these undesired and unacceptable materials before incorporating recycled aggregate in concrete mixes.
- To overcome the D-cracking of pavements, the freeze-thaw of large aggregates should be kept in control.

- Allow the same degree of contamination and potential reactivity approach for recycled aggregate as it is in use for natural aggregates.
- Recycled aggregate is highly angular in nature. It can be used in areas where higher strength is required, but it can also cause reduction in workability. Since workability is another important property of any concrete mix, it should be taken care of if aggregate is recycled.
- Recycled coarse aggregate had also shown higher absorption value than that of virgin aggregate. FHWA guidelines in 1997 indicated its range from 4% to 8% [35].
- It is found that values of moisture content for both recycled and virgin aggregates are almost the same.
- Recycled aggregate concrete has shown good values in terms of durability, abrasion resistance, and soundness.
- Recycled aggregate is more permeable than virgin aggregate.

### 2.13.2 California

Being one of the biggest states in the United States and having a good experience with recycled aggregates, the California Department of Transportation (Caltran) has always received attentions of the research organizations working on recycled aggregate.

According to a survey by FHWA in 2003, Caltran allows use of RAC for specific applications. Initially this figure was up to 50% in the supporting layers of pavements, but now 100% of RAC is allowed [20].

Construction & demolished materials are about 28% of the total waste stream of California, which sums up to about 11 million tons per year. During a survey in 1991, this amount was 11.6%, which are 4,110,526 of the 11,336,608 tons of the total waste.

The recycling rate of this much production is only 57% with the estimated 100 producers of recycled aggregates throughout the state while the rest goes to landfill sites [6, 21].

With the current trends and positive results about usage of recycled aggregates, some communities and the state are trying to enhance its use:

- Recently the City of San Francisco approved that RAC can be used in curbs, gutters, sidewalks, and street bases throughout the city.
- In March 1995, the city of Los Angeles passed a proposal to the state that the road base in all the city projects must use 100% recycled asphalt and concrete except when site conditions or other specifications don't allow its use [21].
- The city of Modesto, California has a purchasing practice for on-site recycling of aggregates.
- It is required in the city of Palo; California that concrete and asphalt in city projects should be recycled.
- Recycled aggregate is used in the local landfill as road base and weather pads.
- The city of Los Angeles, in collaboration with concrete and recycling producers, allows a maximum of 30% recycled aggregate by the weight of total volume of aggregate in some bearing applications [21].
- Use of recycled aggregate was recently approved by the city of San Francisco to be used in non-structural concrete.
- Research is in progress in Orange County for the establishment of specifications for the successful use of RAC.

### 2.13.3 Nebraska

Nebraska State Recycling Association with inputs from The University of Nebraska Center for Infrastructure Research has completed a study and established some standards that are used as guidelines for specifications of recycled aggregates. They claim that it will enable the usage of RAC in municipal, public works, and highway construction [8]. Research work in Nebraska also resulted in acceptance of RAC in many infrastructural works. They also established guideline values (most of them are for subbase course) for some engineering properties:

- Both fixed and mobile crushing plants are in progress in commercial concrete recycling operations in Nebraska. In new crushing machines, most of the recyclers also have the rebar removing technology but still the current applications of recycled aggregate produced in these plants are limited to pavement base courses in highways and airfields, sub grade stabilization, surfacing in parking lots and driveways, pipe bedding for storm, and sewage pipe and gabion fills.
- Due to weather conditions, most of the concrete used in Nebraska in the last 30 years is air-entrained in order to control resistance to freeze-thaw reaction. Therefore when this concrete is demolished, it has good quality and can easily be made useable.
- In Nebraska, selected recycled asphalt has been used in county roads for surfacing to control dust. Recycled asphalt aggregate has also been used in infrastructure construction.
- The Nebraska Department of Roads (NDR), city of Omaha, and city of Lincoln's specifications require an abrasion loss of not more than 45%, based on local conditions and experience, AASHTO and USACE permits it up to 50%. For consistency, 45% is adopted as a limit [8].

- NDR permits the soundness loss up to 14% (16 cycle freeze-thaw) in its specifications [8].
- The absorption of aggregates for base course shall not be more than 5% by weight.
- Nebraska Department of Transportation limited the volume of shale, clay lumps, and other deleterious substances to a total of 2.5% based on the dry weight of the volume retained on sieve # 4. The presence of dust, soft or flaky particles, loams, alkali, organic matter, paper, and wood are not acceptable accordingly [40].

2.13.4 Florida

In Florida, recently a survey was conducted by recycling producers aimed at finding the current practices and methodologies in the state to compare the results with the guidelines and specifications for graded aggregates established by the Florida Department of Transportation (FDOT) [16]. In the survey, sources of concrete for recycling were listed as construction and demolition debris, concrete yards, sidewalks, curbs, slabs, old highways, and roads. Ten of the companies who responded to the survey were estimated to have a total daily production of about 10,000 tons, with the largest one having a daily production of 3000 tons, while the smallest one had up to 40 tons. Most of the companies admitted that they have the mobile crushing plants for recycling of concrete. The current market according to the survey for recycled aggregate is road bases. Other than that, more application areas are pipe bedding, private driveways and parking lots, erosion control, fill, septic tanks and other drainage necessaries, asphalts, and the widening of shoulders and roads.

For the experimental work, a cubic yard RAC was obtained from a plant which is recycling PCC from Interstate 10 near Pensacola, Florida and was tested for gradation, bearing ratio, soundness loss, and compaction.

Results found during these laboratory tests are shown below:

- During the gradation test it was found that the aggregate lacks particles finer than 9.5 mm, which was not according to the FDOT specifications [16].
- The Limerock Baring Ratio test indicated that the recycled aggregate sample possessed a very high bearing value of 238% which was beyond the required FDOT specification of 100% for base courses [16].
- The sample showed a very high soundness loss, which was estimated to be because of its mortar content.
- The test sample of RAC showed a high value of (26% to 37%) abrasion loss compared to natural aggregates. It was estimated because of the coat of hydrated cement over natural aggregates [16].

*Experience by Florida Department of Transportation*

FDOT, in collaboration with the University of Central Florida, reported a project, "Circular Accelerated Test Track (CAAT)". The purpose of the project was to evaluate the properties and performance of a section of a highway constructed with recycled aggregate under actual dual-loading.

Different specimens with mix designs were prepared with different percentages of recycled and virgin aggregates. Important tests required for concrete were carried out. Physical properties of these aggregates are shown in Table 11.

Table 11: Physical Properties of Natural and Recycled Aggregates

| Parameters | Recycled Aggregate | Virgin Aggregate |
|---|---|---|
| Specific Gravity (SSD) | 2.43 | 2.42 |
| Water Absorption (SSD) | 4.36 | 4.1 |
| Unit Weight ($kg/m^3$) | 1410 | 1347 |
| Los Angeles Abrasion (%) | 33.9 | 32.6 |

After research, FDOT established some values for usage of RAC:

- The maximum Los Angeles Abrasion loss is specified up to 50% [50].
- FDOT reported very high soundness test values when sulfate is used. Due to the high value, FDOT specified no value for soundness.
- FDOT allows coal, free shell, and lignite – 1% max, clay lumps and soft and friable particles – 2% max, cinders and clinkers – 0.5% max, organic matters - 0.03% max, chert – 3% max, materials passing sieve # 200 is limited to 1.75% max at the source - and 3.75% max at the point of use as deleterious substances [50].

### 2.13.5 New Jersey

The state of New Jersey is situated in a densely populated part of the country with high commercial and industrial activities. The state authorities started thinking in early 1970s about the recycling of materials, especially concrete, when they realized the unavailability of space to dump this waste. With no other option they had to transfer it to the nearby states.

Crushed glass, street sweepings, and concrete debris from demolition and renovation of buildings and roads were classed as the three main sources of waste. As a result research was carried out by U.S. Department of Transportation, Federal Highway Administration and the New Jersey Department of Transportation (NJDOT) Division of Research and Technology in June 2000, which investigated the suitability of these recycled materials with NJDOT class-A concrete mixture. In the research it was found that the use of recycled aggregate concrete (RAC) as an alternative for the dense-graded aggregate base coarse application is currently about 10% to 15% per year in the state. Keeping in view the technical, economical, and environmental conditions of the state, it can be predicted that this amount will further increase by a huge number in the near future. The report also says that the particles of recycled aggregate possess good shape, high absorption, and low specific gravity, as compared to the particles of the natural aggregates. Recycled aggregate shows no effect on the volume of response of specimens to the temperature and effect of moisture, but the presence of gypsum in the concrete can cause reaction with the matrix in cement because of concentration of sulfate ions [19].

Other findings on RAC in NJ are described below:

- In 1993 Bairagi, Ravande, and Pareek concluded that 50% of natural aggregate can be substituted by recycled aggregate with no effect on the properties of concrete either in fresh or hard stages. As the replacement of natural aggregate by recycled aggregate does not effect the properties of concrete up to certain limit, it is been used more than ever before. It is also allowed in the state to use recycled aggregate as subbase and base course materials in bituminous mixes and base binder courses [40].
- American Concrete Pavement Association (ACPA) allow only 10% to 20% replacement of natural aggregate by recycled aggregate in concrete mixtures [40].

- Due to the non-homogenous nature of recycled aggregate, it does not meet the strict DOT specification for quality.
- Recycled aggregate water requirements and workability with strength of concrete can be compensated by using silica fume or fly ash.
- The excess of recycled aggregate in concrete mixes can cause decrease of toughness, plastic energy capacity, and elastic energy capacity.
- The laboratory testing of the concrete containing 100% recycled aggregate showed that the performance of the mixture is not acceptable generally. Results of compressive strength were in the minimum acceptable range and most of the samples failed the durability tests. The concrete mixes showed deleterious expansion of about 0.02% in 14 days. It was then concluded that it is not suitable to replace 100% natural aggregate by recycled aggregate in Class-A concrete mixes; optimization of the recycled aggregate was proposed [19].
- Using other design mixes, 50% and less, of recycled aggregate showed satisfactory results for compressive strength, modulus of rupture, and chlorides permeability [50].

### 2.13.6 Virginia

Virginia is among those states that started using recycled aggregate in construction projects recently. With strategy to play a neutral role for recycled and natural aggregates, Virginia Department of Transportation (VDOT) started reusing and recycling aggregates. RAC has not been mentioned specifically in the strategic plans of VDOT, yet its statewide usage is allowed with the highways being the most appropriate application of recycled aggregates. VDOT used recycled aggregate as base and subbase material in a $140 million reconstruction program on I-66 in Fairfax and Prince William counties, for which they were awarded the National Concrete Paving Award.[20]

VDOT's experiences with RAC are listed as:

- In collaboration with other states and technical authorities, VDOT established income tax credit on the purchase of recycling machinery with the condition that machinery will be used on the company site.
- For the last 9 years VDOT has used RAC in many projects. They overcame a lot of problems. For example, they concluded that using of saturated recycled aggregate in shoulders will help stop aggregate displacement throughout the mixtures; it will bind together and increase the strength of the concrete.
- Compaction of recycled aggregates with steel rollers will help overcome the problems in the base.
- VDOT recommends the inspection of dumping trucks and improvement of equipment in the processing procedures of recycling.
- VDOT is working in some areas for improvement in the current condition of RAC [20]:
    - Development of standard mix designs of concrete while using recycled aggregate.
    - Effects of recycled aggregate on water in watershed areas when it is used in drains and channels.
    - Improvements in the uncertainty related to use of RAC through different sources.
    - To study the variation in the nature of recycled aggregate in detail.
    - Risk analysis of RAC and improvement research of its long-term performance.
    - Laboratory tests to prove and show the quality of RAC.
    - The current specifications of recycled aggregates and how to enhance them.

2.13.7 Texas

Texas is one of the biggest states with large opportunities for construction. Due to a long construction season, construction activities can be seen throughout the year in Texas. Within this construction cycle, raw materials are produced in huge amount which made the Texas Department of Transportation (TxDOT) plan for reusing it in further construction.

Regarding RAC, TxDOT is using it in different projects, and its current expertise can be judged by the fact that different private industries and municipalities consume more than 60% of the RAC, Texas produces every year [20]. According to TxDOT, using RAC has many benefits and is therefore allowed throughout the state.

TX Dot's experience with RAC is listed below:

- In Texas, it is a bid option in construction contracts for non-structural project concrete to use 100% coarse recycled aggregate. It resulted in consuming most of recycled aggregate flow in Houston specifically [45].
- To control the mix workability problem in one of the projects, it was suggested by the contractor to conduct frequent tests for moisture content and keep them wet before use.
- Earlier, TxDOT allowed use of RAC in pavements and non-structural applications, but after 10 years of experience using recycled aggregate in structural applications, TxDOT has used it in some applications for research purpose and is still monitoring it [45].
- TxDOT allows a minimum Los Angeles Abrasion loss of 40%, magnesium sulfate loss of 18%, and sodium sulfate loss of 12% [50].
- TxDOT requires that recycled aggregate needs to be free of frozen materials such as salt, alkali and vegetables.

- TxDOT is still looking to work in some areas of RAC [20]:
  - Creation of standard acceptable test procedure for recycled aggregate with better results and reduction in uncertainty.
  - Evaluation and methods for the allowable values of lead, asbestos, and other deleterious materials in RAC.

### 2.13.8 Minnesota

Minnesota is on top of the race in experience with recycled aggregate in a sense that it uses almost 100% of the concrete removed from highways during maintenance with the condition that it should meet the requirements of the Minnesota Department of Transportation (MnDOT). It can include up to 3% by mass of asphalt binder from recycled asphalt pavement [45].

MnDOT's mission is to enhance public access to regular important facilities like markets and offices, and also improve transportation facilities to help the locals travel more safely and efficiently. In the currently published Standard Specifications of MnDOT, use of recycled aggregate is allowed throughout the state as coarse aggregate in PCC, base and subbase coarses.

MnDOT is using recycled aggregate in different projects since 1970. Since then it has been used as coarse aggregate in about 20 PCC pavement projects. After using recycled aggregate as coarse aggregate in PCC pavement, MnDOT is trying to incorporate RAC as the primary aggregate base in highway projects [20].

MnDOT experiences with RAC are listed below:

- Recent observations in some projects proved that RAC acts the same way as natural aggregate when used in base or subbase for PCC pavement [20].

- The on-site crushing of aggregate is highly suggested by the authorities in Minnesota, which ultimately helps a lot in the final costs of the projects.
- If best results are needed, it is important, if possible, to wash the recycled aggregate before using it. It removes the excess fines.
- 100% RAC can be used in the construction of filter layers in drainage designs [20].
- MnDOT allows a maximum magnesium sulfate loss of 15% and up to 12% loss of freeze-thaw in 16 cycles. This 16 cycle freeze-thaw test is standard MnDOT method [50].
- The efficiency of recycled aggregate further increases if it does not get washed while used in absence of drainage layers and perforated drainage pipes.
- Report from FHWA and MnDOT also mentions that effluents from RAC are initially highly alkaline. Though its effect gets diluted at a short distance from the drain outlet, its effect on the environment should be taken care of even though it only applies to a very small portion of the area.
- Further areas related to RAC where MnDOT is working are [20]:
    - To develop the performance curves for recycled aggregate
    - Development of database for final product performance constructed with RAC.
    - Research on reduction of cracks' appearance and improvement in base stiffness.
    - Research on long term strength, constructability and performance.
    - Further search on effects of D-cracking and alkaline silica reaction related with recycled concrete aggregate.

### 2.13.9 Ohio

The growing concerns of debris from renovation and construction also hit the state of Ohio. But when starting work to solve the problems associated with the demolished debris, Ohio Department of Transportation (ODOT) was facing some problems like alkaline reaction (high pH of water flowing through recycled aggregate in subbase), tufa formation (calcium deposits), and variations in soundness of the aggregates.

ODOT performed the bucket and box test to find the pH of recycled aggregate with run-off water and compared its value with the system when replaced with natural aggregate concrete. With uncertain results of soundness loss by sodium sulfate test, using freeze-thaw and Los Angeles Abrasion tests, the results were obtained.

The results of bucket and box tests showed the pH value of 10 for recycled aggregate in contact with run-off water, which was above the restricted value of 9, standardized by EPA. Further testing then showed that mixing limestone within a limit of 40% to 60% will produce the pH in aggregates within the limit established by EPA. The box test did not indicate any tufa formation [26].

The soundness test by freeze-thaw showed that recycled aggregate is not as sound as conventional natural aggregate when used as coarse aggregate in concrete mixtures. The test was performed for 160 cycles and it was noted that the majority of loss took place in the first 54 cycles. At this stage, recycled aggregate had 10% to 33% of loss for 1″ sized particles [26].

The soundness loss by Los Angeles Abrasion test also proved the same results as the other aggregates. Comparing to the 21% and 36% soundness loss of virgin aggregate, recycled aggregate concrete showed a soundness loss of 40% and 42% [26].

## 2.14 RAC in Michigan

Being one of the most industrialized states in the country, Michigan always got attention in most of the research projects. Seeing its past experience with recycled aggregate, FHWA chose Michigan with four other states for an in-depth study of recycled aggregate.

In regards of recycled aggregate, Michigan Department of Transportation (MDOT) adopted the strategy for using it if and only if it enhances or equals the performance of natural aggregate quality in the final project. As a further progress, the Standard Specifications of Construction published in 2003, permitted the use of recycled aggregate, but limiting it to coarse aggregate in the Portland cement for curb and gutter, valley gutter, sidewalks, concrete barriers, driveways, temporary pavements, interchange ramps, and shoulders [20].

MDOT used recycled aggregates in the reconstruction of several highways in the early 1980s and the projects ended up with the formation of D-cracking, which was believed due to the poor resistance to the freeze-thawing cycle [12]. Its use in different projects was still undergoing but MDOT put a pause on the use of recycled aggregate when transverse cracks appeared in parts of I-94 and I-75 highways where recycled aggregate was used as coarse aggregate.

MDOT allowed its use again in 1991 when it was proved through the research report, "Uses of Recycled Aggregate in Michigan" by the University of Michigan and Michigan State University that those cracks were not only because of recycled aggregate, but design of base, uniformity of the foundation layer, stiffness of the sub grade materials, thickness of the pavement layers, and that the surrounding temperatures were other causes of transverse cracks, faulting, and spalling [20].

Replacement or substituting recycled aggregate with natural aggregate can be widely seen in Michigan since the early 1980s. Twenty-six projects have been constructed with about 650 lane miles of PCC pavements. It has also been used in several portions of M-10, I-75, I-94, I-95, I-96, US-41 in the Upper Peninsula, and in other three projects in the Detroit area. While using it in US-41 in the Upper Peninsula, it resulted in a total savings of $114,000 on a project of $3 million [20].

MDOT experiences with RAC are listed below:

- Quality assurance and control with recycled aggregate will always play an important role in all the projects. It should be controlled and monitored.
- It was found in research that recycled aggregate increases the foundation stiffness and reduces slab tension with additional reinforcement when deformed wire mesh and hinge joints are used.
- MDOT does not have sodium or magnesium sulfate soundness requirements for recycled aggregates in its specifications for use in PCC. But, its specifications require freeze-thaw procedure under ASTM 666 testing method in every project. Thirty cycles are to be performed where recycled aggregate is used in PCC.
- MDOT limits contamination of other material like joint sealants, bituminous patches, and base layer aggregates up to 3% by weight [50].
- MDOT is further looking for research in several areas of recycled aggregate [20]:
    - Further improvement in the design mixes where recycled aggregate is being used as coarse aggregate with some percentage or a whole.

- Effects of recycled aggregate when it is used in applications of drainage system. It includes bedding for pipes, effect on watershed areas, bleaching of the water table, and other possible effects on the water carrying conduits.
- To detect the actual value of resilient modulus to see the further effect.
- To document experiences with recycled aggregate in different applications, which will be helpful in further work.
- To establish the same design specifications for use of recycled aggregate throughout the state after coming up with standard tests and results.
- To prove the test results and see their effect practically carried out through demonstration projects. It will also clear the ideas of comparing results with virgin aggregate.

2.14.1 Calhoun County Road Commission (MI)

Calhoun County Road Commission is one of the agencies of Calhoun county community development (cccd) in Marshal, Michigan which is working to provide infrastructural and other facilities to the locals. Road commission has a special solid waste/recycling unit. They have used recycled aggregate for construction and repair of small dirt or gravel roads and shoulders, rip raps, driveways, and other numerous projects throughout the county. They also sell them in open market if someone needs it. 33% percent of the material that the commission produced in 2001 was sold, while the rest was used in their work [64].

The present approximate usage of recycled aggregate in their own work is 25% in shoulders, 70% in road bases, and 5% for other uses [64]. The commission is intending to use it as a premium road base in the future. This department also aims to reduce the problems that have been created by waste and is therefore working to recycle the waste, especially debris obtained from pavement repair and construction, to reduce the burden on the county.

According to the commission, they did not follow any specifications or guidelines for the recycled aggregates they used, and they have not heard of any problems with them to date. The commission also provided recycled aggregates for testing and research while working on this study.

# CHAPTER 3

# OPTIMIZATION

## 3.1 Introduction

Recycled aggregate is exposed to all kinds of detrimental environmental conditions; therefore, a porous matrix is formed around it. The development of this matrix makes it a high water absorption material. As a result more water or water reducers are required to be added to the concrete where recycled aggregate is used in order to make it as workable as concrete containing conventional aggregates. But these processes are flawed because the addition of water makes concrete weak while water reducers will increase the cost. Some other alternatives are therefore needed to be sought that do not affect rest of the properties of the concrete.

Alternatives can be replacing recycled aggregate up to some extent for another aggregate or adding other materials like silica fume, fly ash or fibers etc. It was found during literature that 100% replacement of natural coarse aggregate with recycled aggregate will not give the same quality and durability to the final structure but partial replacement can provide satisfactory results.

To make the picture clearer of replacing aggregate by recycled one the next point was its optimum amount. This is the amount that can substitute conventional aggregate and does not affect the important and essential properties of the concrete. For this purpose several proportions of recycled to virgin aggregates were used in concrete mixes. Workability and compressive strength were chosen as the evaluation criterions for this optimization phase of concrete mixes.

Source of the recycled aggregate, used for laboratory testing was a torn up portion of I-69 in Calhoun County, which was recycled by Balkema Construction of Sodus, MI and was provided by Calhoun County Road Commission.

## 3.2 Recycled and Virgin Aggregates

The economic benefits of recycled aggregate cannot be underestimated in the areas where natural aggregate is scarce. The usual sources of this aggregate are demolished parts of highways and other structures, which is one of the reasons that it contains a lot of dirt and fine materials. Therefore, it is suggested to stockpile recycled aggregate after recycling and use the top portion of the stockpile each time.

Since source of the recycled aggregate used for experiments in this research study was also a demolished highway; it therefore had fine materials such as dirt and large chunks of rocks. It also contained soil, particles of bitumen, as well as crushed and natural rocks. Almost all the particles were coated with dirt, clay, and dust.

The particle shape and outer surface texture of coarse aggregate influences the properties of concrete mix [57]. Generally, the rough and angular aggregates require more water and cement for workability and maintaining water to cement ratio as compared to round aggregates. Recycled coarse aggregate used for laboratory testing contained aggregates of rounded, angular, and irregular textures. It was sieved to remove most of the dirt, fine materials, and to get a well-graded coarse aggregate for the concrete mixes. After removing the fine particles and large rocks, a well-graded recycled coarse aggregate was obtained. Comparison of recycled aggregate before and after sieving is shown in Figures 20. The weight of recycled aggregate before and after sieving was compared to the normal weight of virgin coarse aggregate. The un-sieved recycled aggregate contained about 40% of undesired materials, which can affect the results, quality, and durability of concrete.

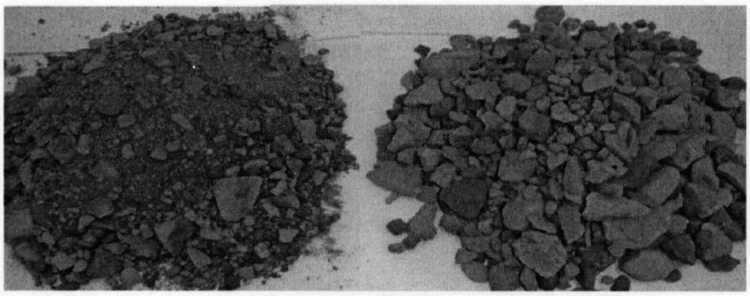


Figure 20: Recycled Aggregate Before and after Sieving

To analyze the behavior of recycled aggregate and compare its physical values with those of virgin aggregate, some basic physical characteristics of both the aggregates were calculated. They are sieve analysis, bulk specific gravity, bulk specific gravity (SSD), apparent specific gravity, water absorption, and moisture content. Apart from water absorption and moisture content, the remaining values differ by a small margin.

### 3.2.1 Sieve Analysis

Using the standard test method for sieve analysis of coarse aggregate ASTM C 136, sieve analysis both for recycled and virgin aggregates were performed as shown in Figure 21. The gradation curve shows that recycled aggregate has more fine materials than virgin aggregate. More fine materials cause non homogeneity in aggregate sizes which can result in high shrinkage, more water requirements, and poor workability in concrete [57].

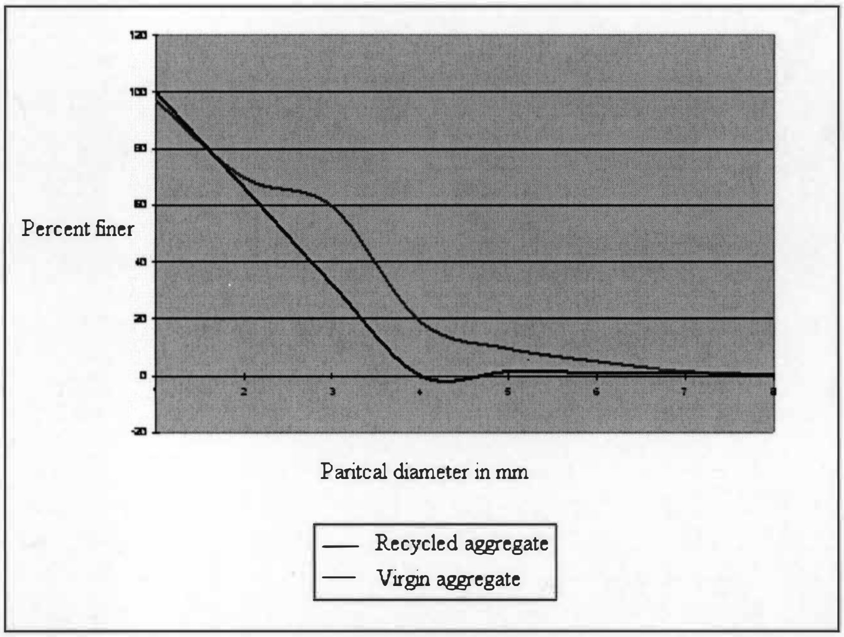



Figure 21: Gradation Curves of Recycled and Virgin Aggregates before Sieving

To bring the performance of recycled aggregates close enough to that of virgin aggregates and within the limits of ASTM, it was sieved for 1" maximum and 3/8" minimum aggregates' sizes. After the removal of most of the dirt, big chunks, and fine particles during sieving, the sieve analysis of aggregate was performed again. The gradation curve of the sieved recycled aggregate, as shown in Figure 22, was much closer to that of virgin aggregate as compared to the previous and un-sieved recycled aggregate. Comparing this gradation with standard ASTM curve shows that some grades are still missing within recycled aggregate. Virgin aggregate curve is in the limits of ASTM while the grades missing in recycled aggregate shows a gap in the gradation curve after sieving (Figure 22).

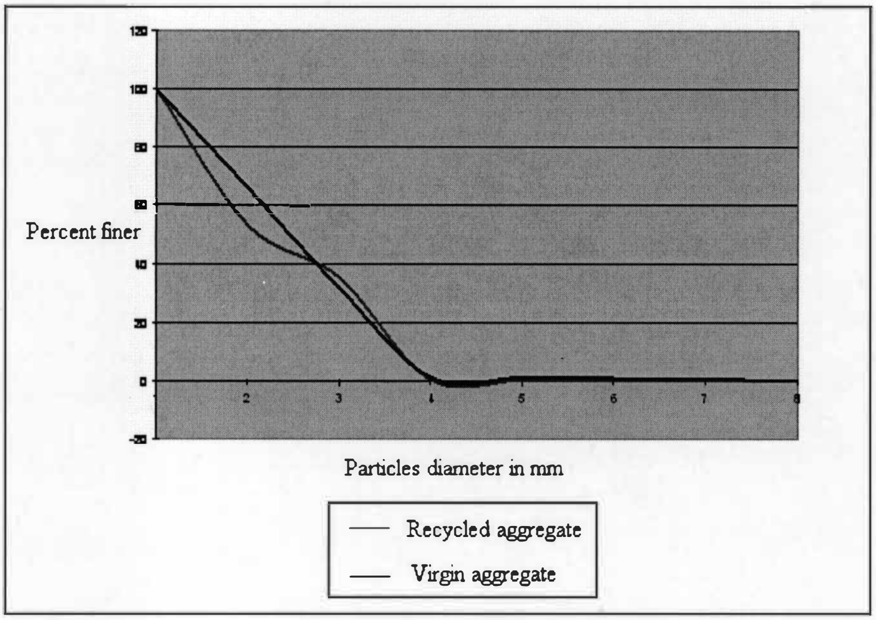



Figure 22: Gradation Curve after Recycled Aggregate is Sieved

### 3.2.2 Specific Gravity

Specific gravity of aggregates can be defined as the ratio of its mass to the mass of an equal absolute volume of water [57]. Following ASTM C-127 standard methods, the values of different specific gravities for both recycled and virgin aggregates were calculated. These values were similar with small variation and were consistent with results found in the literature.

### 3.2.3 Water Absorption and Moisture Content

Values of moisture content and water absorption play important role to determine the mixing water in concrete. Therefore these properties were calculated and considered during mix design. Both the aggregates were considered at surface saturated dry (SSD) conditions.

Moisture content tests for both recycled and virgin aggregates were performed using ASTM C-566 method. It was found during the test that recycled aggregate requires more water when mixed within concrete than a freshly blended virgin or natural aggregate.

A comparison of physical properties for both aggregates is shown in Table 12.

Table 12: Comparison of Physical Properties of Aggregates

| Physical properties | Recycled aggregate | Virgin aggregate |
|---|---|---|
| Bulk specific gravity | 2.27 | 2.49 |
| Bulk specific gravity (SSD) | 2.33 | 2.54 |
| Apparent specific gravity | 2.55 | 2.67 |
| Water absorption | 6.5 % | 3.2 % |
| Moisture content | 10 % | 8 % |

As compared to recycled aggregate, virgin aggregate used in the optimization of recycled aggregate in laboratory testing, consisted of crushed stone with a maximum size of 1". It was hard, clean, strong, durable, and mostly angular in texture as shown in Figure 23. The smooth gradation curve in the gradation figures also shows the well-graded distribution of the aggregate.

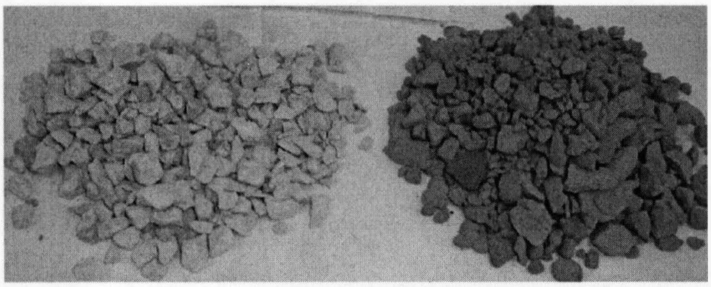


Figure 23: Sieved Virgin and Recycled Aggregates as Used in the Mixes

### 3.2.4 Coarse and Fine Aggregate Ratios

According to ACI codes, a ratio of 55/45 for coarse and fine aggregates gives satisfactory results [57]. For best results, this ratio was adopted in the earlier trials, however, due to large surface area and a difference of water absorption of fine to coarse aggregate, it was noted that the concrete was dry and needed some additional water or water reducers.

To overcome this problem, with no other changes in the components of the concrete, the coarse to fine aggregate ratio was changed from 55/45 to 60/40. With this increase in the weight, fine aggregates made the concrete much more workable then the previous ratio and requirement of extra water or water reducers was also solved.

## 3.3 Concrete Mixing

The basic components of the trials mixes during optimization were Portland cement, fly ash, water, recycled coarse aggregate, virgin coarse aggregate, fine aggregate and water reducers. They are shown in Figure 24.

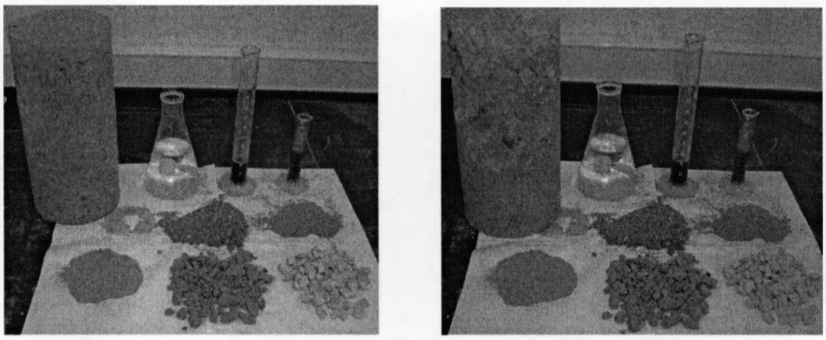


Figure 24: Components Combined to Form Concrete

All the concrete mixes were designed for 4000 psi strength. Also a 3" slump and water to cement ratio of 0.4 (0.42 in a few mixes) were designed and maintained to confirm to ACI codes for structural applications [57] throughout the experimental work.

The concrete mixer used to mix all the materials of concrete was cleaned with sharpening blades before every mix. The general procedure was to mix half of the fine aggregate thoroughly with water before the addition of half of coarse aggregate. Then, the remaining fine and coarse aggregates were added. Fly ash was the final material to be mixed in with the aggregates before the cement was introduced. Water was added to the mix proportionally after the addition of every component. Sufficient time was given to blend all the materials to ensure the formation of homogenous mixture. Once the concrete was properly mixed, it was poured in 6"x 12" and 4" x 8" standard plastic cylinder molds as shown in Figure 25 and was cured.

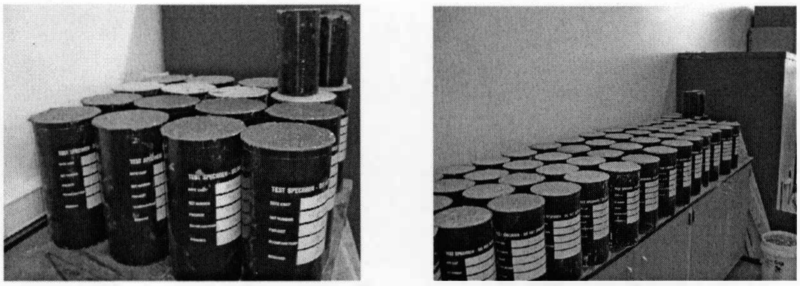


Figure 25: Concrete Samples at Different Stages

These concrete specimens were then tested for compression test at different ages. Different stages of mixing and pouring of concrete are shown in Figure 26.

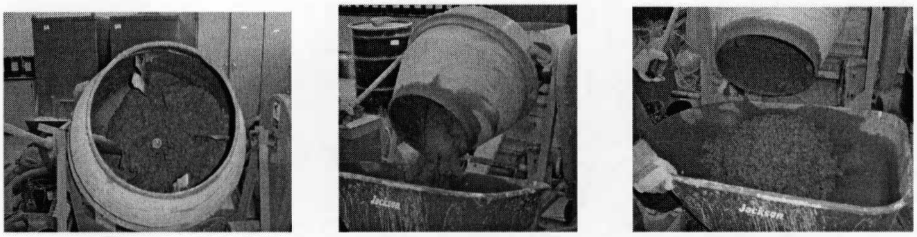


Figure 26: Mixing and Pouring of Concrete for Samples

### 3.3.1 High Cement Content Mixes

To evaluate the behavior of concrete with recycled aggregate as coarse material in applications where high strength is required, mixes with high cement contents (high strengths) were cast. Earlier, during these mixes, Type I cement was used as cementitious material for the design of 4000 psi strength. It is ordinary cement and is generally used for all purposes where special properties for the final products are not required [57]. During these trials, water reducers were introduced for dry concrete mixes which was helpful in decreasing the water absorption capacity of the recycled aggregate.

To test the behavior of cement in combination with recycled aggregate in some of the trials mixes, high strength (Type III) cement was used. This cement provides strength at very early stages. It has same similar chemical and physical properties to Type I cement, but is grounded finer. It is used in structures when forms are required to be removed early or when structure is intended to be used sooner [57].

To make the whole process more economical but of good strength in the next phase, fly ash was used in the mixes. Following the design specifications of MDOT, the amount of fly ash was limited to 25 % of the weight of the cement. Fly ash is very economical as compared to cement and is easily available.

### 3.3.2 Lower Cement Content Mixes

To evaluate the use of recycled aggregate in applications where high strength is not required, mixes of low cement contents were tried. The same methodology as adopted in higher cement mixes was used here.

The general ratios of the aggregates with fly ash and water reducers used during optimization process are listed in Table 13.

Table 13: Ratios of Aggregates in Concrete Mixes

| Recycled Aggregate (%) | Virgin Aggregate (%) | Fly Ash | Water Reducers (ml) |
|---|---|---|---|
| 100 | 0 | 25 % of cement | 20 |
| 30 | 70 | 25 % of cement | 20 |
| 50 | 50 | 25 % of cement | 20 |
| 30 | 70 | 25 % of cement | 20 |
| 0 | 100 | 25 % of cement | 20 |
| 100 | 0 | 0 | 20 |
| 30 | 70 | 0 | 20 |
| 50 | 50 | 0 | 20 |
| 30 | 70 | 0 | 20 |
| 0 | 100 | 0 | 20 |

## 3.4 Optimization

After calculating the physical properties of aggregate, the next phase of the experimental work was optimization - to find out the optimum amount of coarse aggregate that can be replaced by recycled aggregate with fewer effects in durability, strength, and other physical and mechanical properties of concrete. For optimization, several concrete mixes with different proportions of recycled to virgin aggregates were mixed. The selection of this optimum amount of recycled aggregate was based on results of its behavior in workability and compressive strength.

### 3.4.1 Workability

Workability was one of the evaluation criteria established to find the optimum amount of recycled aggregate within a concrete mix. Slump loss was therefore measured after every mix to compare the results with the designed slump.

The aggregates were considered at SSD condition and to maintain the designed water to cement ratio the water requirement of concrete increased with increase in the proportion of recycled aggregate.

Slump losses for different proportions of recycled aggregates and contents of cements are shown in Table 14.

Table 14: Workability of Concrete Mixes

| Proportion of R.A (%) | Designed slump (in) | Achieved slump (in) | | |
|---|---|---|---|---|
| | | High cement content | | Low cement content |
| | | With fly ash | Without fly ash | |
| 100 | 3 | 6.5 | 3 | 5 |
| 75 | 3 | 5.75 | 2.5 | 4 |
| 50 | 3 | 2 | 1.6 | 2.5 |
| 30 | 3 | 2 | 0.2 | 3 |
| 0 | 3 | 0 | 0 | 2.5 |

Slump losses for different proportions of recycled aggregate and cement contents are shown in Figure 27.

Figure 27: Different Workabilities were Noted During Trial Batches

3.4.2 Compressive Strength

Compressive strength is the maximum resistance to applied axial loads on the concrete specimens after they are cured for certain days. This test method is used to determine the unconfined compressive strength of cylindrical concrete specimens [57]. This property of concrete was selected as the second evaluation criteria for the optimized concrete mix with the different proportions of recycled aggregate and virgin aggregates. Compressive tests were performed under the designation of C 39/C 39M-01 of ASTM standard specifications.

It was noted during literature review that most of the concrete with recycled aggregate had shown strength up to 6000 psi. Therefore during this research study, a compressive machine with the capacity of 250 k was used. But in order to compare the results with 100% virgin aggregate compressive strength of some specimens went up to the limits that a machine of 400 k was brought in to use. Both machines with the specimens are shown in Figure 28 and Figure 29.

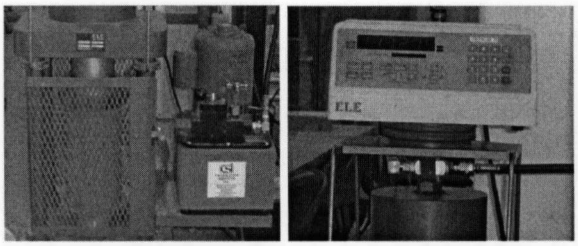


Figure 28: 250 k Compression Machine

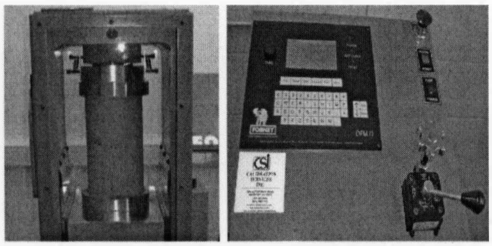


Figure 29: 400 k Compression Machine

*Compressive Strength of High Cement Content Specimens*

RAC showed adequate strength and it can be noted from strength tables (Table 3.4) that concrete got strong with reducing either proportions of recycled aggregate or increasing cement.

These specimens, when inspected after curing, were noted to be solid, hard, and homogenous in shape. Compressive strength tests also showed that higher the proportion of recycled aggregate, the lower the strength. It was also concluded that desired results of high strength can be obtained by substituting 30% to 50% of coarse aggregate in concrete with recycled aggregate.

Strength of recycled aggregate was also judged from the failure types, when it was noted that most of the fracture types were shear, cone, or a combination of both. This proved that recycled aggregate was strong enough to be broken before the cement failure occurred.

Different failures for high cement content specimens are shown in Figure 30.

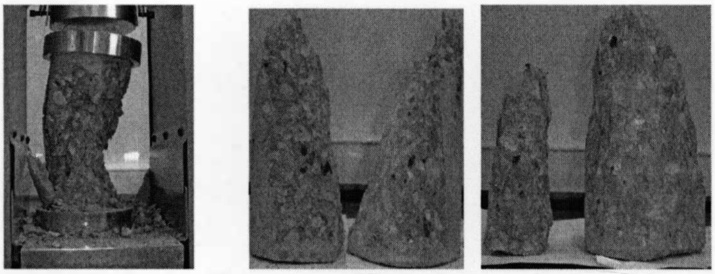


Figure 30: Different Failures of High Cement Content Specimens

*Compressive Strength of Low Cement Content Specimens*

Behavior of recycled concrete as a substitute coarse material for natural aggregate with low cement content was tested during this series of trial mixes. Concrete mix designed for these low cement content concrete trials was based on MDOT's specifications for overlay mix designs. With the reduction of cement content, lower strengths were noted as compared to the previous phase, but were still within an acceptable range.

Literature review revealed that range of 20% to 50% [45] replacement of recycled aggregate in concrete gave satisfactory results, which was concluded during this series of trial mixes. Comparing the evaluation criterions proved that replacement of natural aggregate by recycled aggregate up to 50% gave good results.

Values of compressive strength for different aggregates are shown in Table 15.

Table 15: Compressive Strength of Concrete Mixes

| Proportion of R.A (%) | 28-day compressive strength (psi) | | | 56-day compressive strength (psi) | | |
|---|---|---|---|---|---|---|
| | High cement | | Low cement | High cement | | Low cement |
| | With fly ash | w/o fly ash | | With fly ash | w/o fly ash | |
| 100 | 5989 | 4342 | 3633 | 6109 | 4452 | 3856 |
| 75 | 6405 | 5056 | 4058 | 6418 | 5281 | 4261 |
| 50 | 7446 | 6413 | 5950 | 7490 | 6572 | 6072 |
| 30 | 7694 | 6872 | 6118 | 7781 | 6983 | 6324 |
| 0 | 7756 | 7540 | 6756 | 7826 | 7713 | 6911 |

The fracture types of these specimens were not as good as those of high cement concrete samples, and most of the samples failed under shear fracture types, but the recycled aggregates of concrete were noted to remain unbroken after the samples were fractured, as shown in Figure 31.

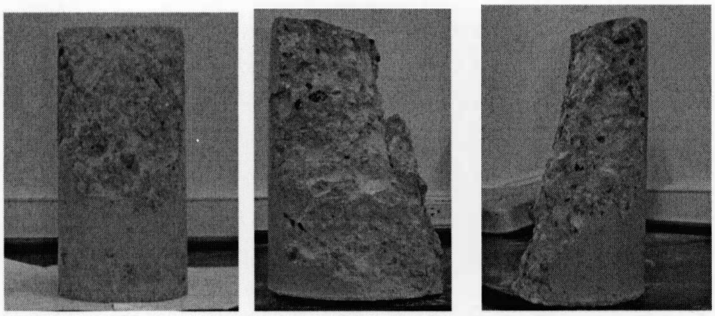


Figure 31: Different Failures of Low Cement Content Specimens

Based on the comparison and evaluation of all the data and results in the light of workability and compressive strength of concrete mixes with the practical applications and feasibility, the mix design of low cement content with the substitution of 50% coarse aggregate by recycled aggregate was chosen as the optimized mixture. The materials of 1 $ft^3$ concrete mix are shown in Table 16.

Table 16: The Optimized Mix

| | |
|---|---|
| Type I cement | 15.6 lbs |
| Fine aggregate | 47.5 lbs |
| Recycled aggregate | 33.2 lbs |
| Virgin aggregate | 33.2 lbs |
| Fly ash | 5.3 lbs |
| Mixing water | 9.5 lbs |
| High range water reducer | 10 ml |

## 3.5 Chapter Summary

Based on the experimental results of this research study, 50% substitution of aggregate with recycled aggregate produced the targeted results. Secondly, it was noted during literature that most of the work done was on 30% of recycled aggregate. The results were satisfactory. Thirdly, seeing the practical application and economical feasibility, this mixture of low cement content gave satisfactory results as well. Still, if it is to be used in areas where high strength is required, the same proportion with high cement content can be used. Moreover, in light of the set evaluation criterions of workability and compressive strength for all the concrete mixtures, this mixture is strongly recommended for use in structures and further evaluation.

# CHAPTER 4

# EVALUATION OF MECHANICAL PROPERTIES OF THE OPTIMIZED MIX

## 4.1 Introduction

In this phase, the optimized concrete mix with 50% recycled aggregate has been tested extensively to evaluate its mechanical properties. Material testing was conducted in accordance with the ASTM and AASHTO specifications and the results were compared with the values found in the literature for recycled aggregate and conventional concretes.

The evaluation of mechanical properties of the optimized recycled aggregate mix included the determination of the compressive strength, flexural strength, freeze and thaw resistance, drying shrinkage and modulus of elasticity.

## 4.2 Observations

During casting of the concrete mix, following observations were noted:

- Due to high viscosity, mechanical vibrators were used while dumping concrete in the formworks. It was helpful in filling the formworks evenly which resulted in specimens of the designed dimensions
- None of the vibrators were used in the tests that is not allowed in ASTM specifications, like workability tests or filling of cylinders for compression tests
- The concrete specimens were filled with surfaces finished nicely. They were covered with plastic that helped in keeping them damped and gave enough time to chemical reaction between cement and water
- Due to continues process and less wastages, the process of pouring was finished in time

## 4.3 Fresh Stage Test

The only test that was run during fresh stage of concrete was slump test.

### 4.3.1 Slump Test

Since the adjustment of the entire concrete mix was dependent on the slump loss test, this test was very crucial and was run very carefully. But due to the precautions taken and good communications with the concrete supplier, this test was according to the designs. The slump was noted to be 3.2" while the designed slump was 3". After passing this test, all the formworks for the specimens were filled and kept covered.

## 4.4 Mechanical Properties

After curing of concrete so that the surface of the specimens do not get damaged, they were removed from formworks after 24 hours of casting. As initial precautions were taken care of, there were no problems in removing the specimens from the formworks. But due to the use of vibrators in some of the specimens' formworks, a few of the samples got dried in undesired edges which were discarded. Still most of the specimens were well in shape with sharp edges. All the concrete samples were put in the water tank for curing. Samples during curing period are shown in the water tank in Figure 32.

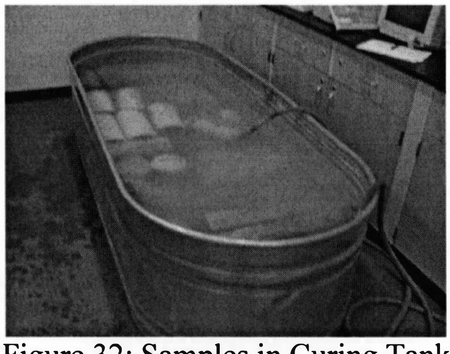


Figure 32: Samples in Curing Tank

All the tests were conducted according to the ASTM specifications on the specified days and within the required conditions. Description of material testing, test specifications, test specimens, the number of specimens tested in each category and the test date since casting are presented in Table 17.

Table 17: Summary of Material Testing

| Test | Test specifications | Specimen size | No. of specimens per test | Test date since casting |
|---|---|---|---|---|
| Compressive strength | ASTM C 39-99 | Cylinder 6"x12" | 3 | 3,7,14 and 28 days |
| Modulus of elasticity | ASTM C 469-94 | Cylinder 6"x12" | 3 | 7,14 and 28 days |
| Stress-strain relation | ASTM C 469-94 | Cylinder 6"x12" | 3 | 7,14 and 28 days |
| Flexural strength | ASTM C 78-94 | Beam 5.5"x5.5"x 21" | 3 | 7,14 and 28 days |
| Drying shrinkage | ASTM C 157-99 | Beam 4"x 4"x24" | 4 | Starts after 7 days |
| Rapid freeze and thaw resistance | ASTM C 666-97 Procedure “A”- Freezing and thawing in water | Prism 3"x 4"x16" | 8 | Starts after 14 days |

All the tests for hardened concrete specimens are discussed in detail with the observations and results noted.

### 4.4.1 Compressive Strength

For compressive strength, concrete specimens were given enough time till all the water was drained off when they were removed from the water curing tank. These tests were conducted at 3, 7, 14 and 28 days. Each time 3 samples were tested and the mean of them was considered as the final value.

Strength development for the concrete specimens of recycled aggregate and its comparison with values found in literature and conventional concrete that were noted during the phase of optimization are shown in Table 18.

Table 18: Compressive Strength with Time

| Age of concrete (days) | Strength recycled aggregate specimens (psi) | Values found in literature (psi) | Strength of conventional concrete (psi) |
|---|---|---|---|
| 3 | 3928 | | |
| 7 | 4220 | | |
| 14 | 4960 | 4326 [19] | |
| 28 | 6280 | 4824 [19] to 5520 [60] | 6756 |

The designed strength of the concrete was 4000 psi with water to cement ratio of 0.42. The results in Table 18, indicates that concrete developed almost the designed strength in the first 3 days. At the end of the 7-day, it crossed over the designed limit and till 28 days, it developed about 55% more strength than the designed one.

The values found in literature for the concrete having 50% recycled aggregate matches the values till 14 days. The same study showed lower values for the 28-day compressive strength [19]. Another study found the values near to the results of this study, but in that case the proportion of recycled aggregate was 75% [60].

The graphical representation of the strength development of the concrete containing 50% recycled aggregate with the designed strength of 4000 psi and its comparison to the conventional concrete of the same designed strength is shown in Figures 33.

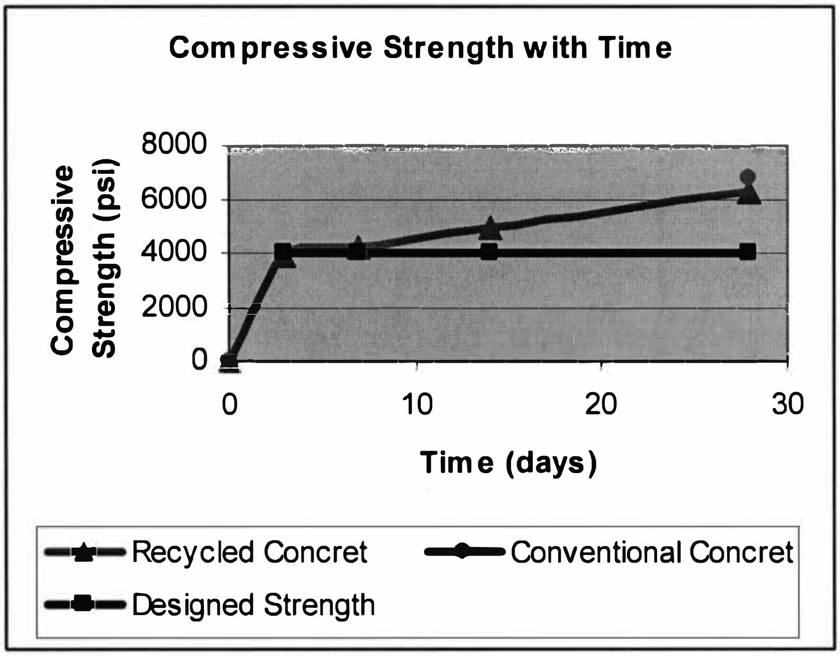



Figure 33: Compressive Strength Development of Concrete with Time

Figure 33 shows that recycled aggregate develops almost the same strength and in the same way as other conventional concretes do.

During compression strength, recycled aggregate was noted to remain unbroken through out after the specimens got fractured. It was also observed that most of the cylinders fractured either in the shape of shear or cone or in combination of both of them.

These characteristics show that recycled aggregate is of enough strength. Some of the samples after crushing under axial loads during this phase of the study are shown in Figure 34.

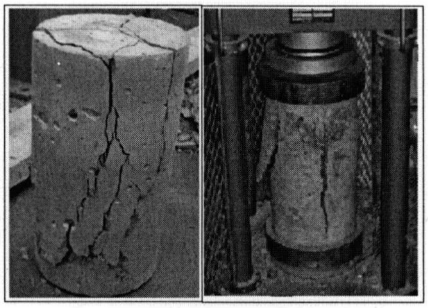


Figure 34: Failure Modes of Recycled Aggregate Concrete

4.4.2 Modulus of Elasticity

As shown in the summary Table 4.1 for the tests, this test was performed at different days following standard specifications of ASTM C 469-94. According to the specifications, 6" x 12" cylinders were tested to calculate Chord Modulus of Elasticity of recycled aggregate concrete at 7,14, 21 and 28 days.

The values of Chord modules of elasticity obtained at different ages of recycled aggregate concrete with the comparison of values found in literature are shown in Table 19.

Table 19: Modulus of Elasticity of Recycled Aggregate

| Age of concrete (days) | Chord modulus of Elasticity ($10^3$ psi) | ACI equation $E_c = w_c^{1.5} x\ 33 (f'_c)^{1/2}$ ($10^3$ psi) | Values found in literature ($10^3$ psi) |
|---|---|---|---|
| 7 | 3978 | 3743 | |
| 14 | 4187 | 4058 | |
| 28 | 4305 | 4566 | 4420 [60] |

No values of Modulus of elasticity were found for any other day, but 28. The values shown in the Table 19 from literature is for the concrete having 75% recycled aggregate but is still comparable. The setup used for this test is shown in Figure 35.

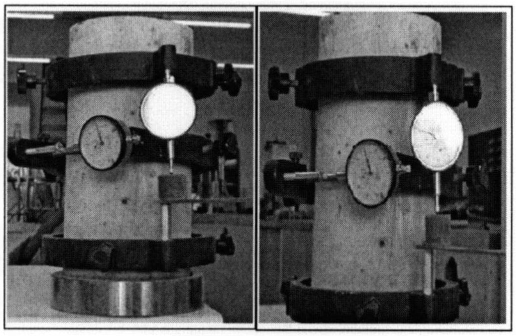


Figure 35: Setup for Test of Modulus of Elasticity

Since no data was found in literature, the ACI equation for the calculation of modulus of elasticity was also used to calculate the values. The ACI equation is as:

$$E_c = w_c^{1.5} \times 33 (f'_c)^{1/2}$$

In this equation, where $w_c$ is the unit weight of concrete (lb/ft$^3$) and $f'_c$ is the specified compressive strength of concrete (psi), the Modulus of elasticity ($E_c$ in psi) for the respective days are calculated and is shown in Table 19. The values in Table 19, using ACI equation are comparable to those calculated using the ASTM C 469-94.

### 4.4.3 Stress-strain Relation

With the application of axial load, the changes in length and strain in the specimens were noted. These changes in specimens were monitored for different ages of concrete. It was observed that the 7 day relation was not uniformed however the values for 14 and 28-day tests were satisfactory. Little deviations were also noted at the earlier stages which were because of the initial surface contact between sample and machine, gauges set-up errors, mistake in reading the gauge and non-uniform application of loads.

Stress-strain relationship for recycled aggregate concrete at certain days is shown in Table 20 and its graphical representation is given in Figure 36.

Table 20: Stress-strain Relationship for Recycled Aggregate Concrete at Different Days

| Stress (psi) | 7-day strain (micro strain) | 14-day Strain (micro strain) | 28-day Strain (micro strain) |
|---|---|---|---|
| 100 | 165 | 160 | 170 |
| 500 | 225 | 240 | 230 |
| 1000 | 320 | 330 | 325 |
| 1500 | 405 | 420 | 415 |
| 1688 | 460 | ----- | ----- |
| 1984 | ----- | 510 | ----- |
| 2000 | ----- | ----- | 520 |
| 2500 | ----- | ----- | 600 |

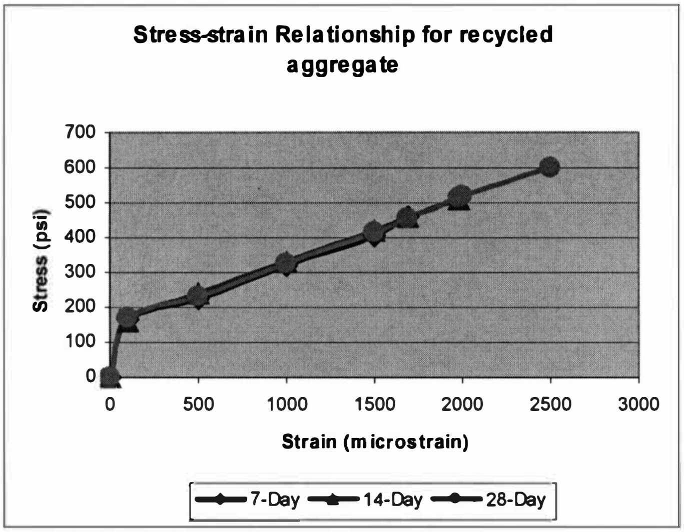



Figure 36: Stress-Strain Curve for Recycled Aggregate Concrete

The axial load applied on concrete specimens for measurements of strain was 40% of the compressive strength of concrete at that specified day. The stress to strain behavior of recycled aggregate resembles that of conventional concrete which is normally a linear ascending branch [60].

### 4.4.4 Flexural Strength

To test the recycled aggregate concrete for flexural strength, concrete beams with dimensions 21"x 5.5"x 5.5" were subjected to third point loading at 7, 14 and 28 days after casting and curing. During the tests, the applied load was recorded at the time cracks started in the beam. It was noted in all the tests that the beam cracked within the middle third of the span length in the tension surface and the failure of the beams were then very sudden.

The set up used for calculation of flexural strength is shown in Figure 37.

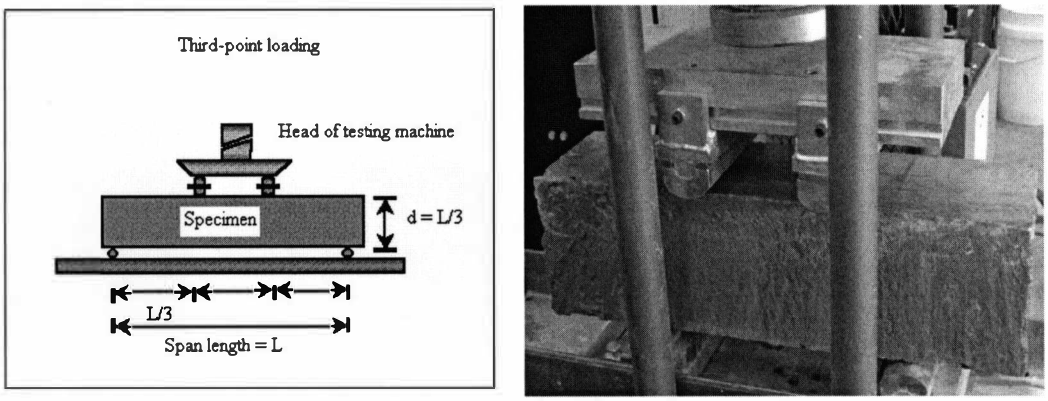



Figure 37: Test Setup for Flexural Strength

To analyze the behavior of recycled aggregate concrete in flexural, modulus of rupture was calculated at different days as mentioned earlier. According to ASTM C 78-94 specifications, since the fracture occurred in the tension surface and within the middle of the span length, the following formula was used to calculate modulus of rupture [56]:

$R = PL/bd^2$

Where:

R = modulus of rupture (psi)

P = maximum applied load indicated by the testing machine (lb-in)

L = span length (in)

b = average width of specimen at the fracture (in)

d = average depth of specimen at the fracture (in)

To analyze further, the 28-day modulus of rupture value is compared with specified ACI code for modulus of rupture. The ACI code used is:

$R = 7.5\,(f'_c)^{1/2}$

Where,

$f'_c$ is the 28-day compressive strength of the concrete

Using the above mentioned formulae, R is calculated at different ages of recycled aggregate concrete. Values calculated and found in literature are shown in Table 21.

Table 21: Flexural Strength for Recycled Aggregate Concrete with Time

| Age of concrete (days) | Modulus of Rupture (psi) | Values found in literature (psi) | $R = 7.5\,(f'_c)^{1/2}$ |
|---|---|---|---|
| 7 | 665 | | |
| 14 | 710 | | |
| 28 | 793 | 653 [60] | 595 |

The difference in values for 28-day flexural strength calculated and found in literature is because the literature value is for the concrete having 75% recycled aggregate in proportion of coarse aggregate. This value is 724 psi for concrete with 25% recycled aggregate and 604 psi for 100% recycled aggregate [60].

Table 21 shows that 28-day modulus of rupture value found during test is higher than the value calculated using ACI code.

### 4.4.5 Drying Shrinkage

One of the problems associated with recycled aggregate concrete, found in literature, was its high tendency towards creep and drying shrinkage [54]. To evaluate this property of recycled aggregate concrete samples of dimensions 24"x 4"x 4" were cast and cured in water tank. Four of the samples were removed from the water tank after a full 7-day curing and were kept under observation for shrinkage without application of any load. The concrete samples kept under observation are shown in Figure 38.

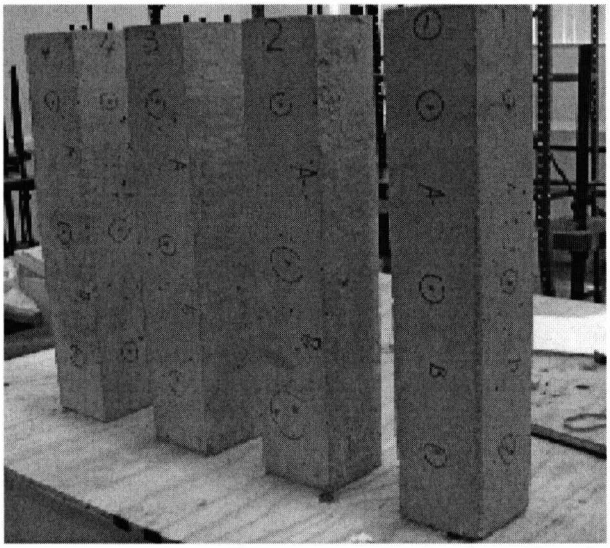


Figure 38: Concrete Specimens for Drying Shrinkage

To monitor the shrinkage, demac points, spaced at approximately 8" were attached along the longitudinal direction on two opposing faces of each sample, as can be seen in Figure 38 and were kept under room temperature of approximately 70 $^{0}$F. Initial strain readings were noted after mounting the demac points and as careful observations were needed for this property of recycled aggregate concrete, shrinkage readings were then taken everyday for the first week, three times a week for the second one and then once a week.

These concrete samples were monitored for about 2 months. During monitoring it was noted that recycled aggregate has a higher tendency towards drying shrinkage. The values noted up to the first 3 weeks for shrinkage were higher than the ACI-209 predicted values for normal concrete. Later on, however the shrinkage strain values came under the predicted limits of ACI.

The formula used to calculate the ACI-209 predicted strain is [63]:

$Sh. = [((t-t_c) / (b + (t-t_c)] / k_{ss} \times k_{sh} \times E_{shu}$

Where:

$Sh$ = shrinkage

$t$ = age of concrete after casting (days)

$t_c$ = age of concrete drying commenced (days)

$b$ = constant in determining shrinkage strain, depends on curing method (35 for moist-cured concrete)

$k_{ss}$ = shape and size correction factor for shrinkage

$k_{ss} = 1.14 – 0.0035 (V/S)$ ($V$ = volume & $S$ = surface of specimen)

$k_{sh}$ = relative humidity factor for shrinkage ($1.4 – 0.01^* H$) ($H$ = humidity in between 40% to 80%)

$E_{shu}$ = ultimate shrinkage strain ($780 \times 10^{-6}$) (mm/mm)

Measuring of shrinkage strain in one of the samples and the measured values while monitoring the samples of recycled aggregate concrete with the predicted ACI-209 strain for concrete are shown in Figure 39 and Table 22.

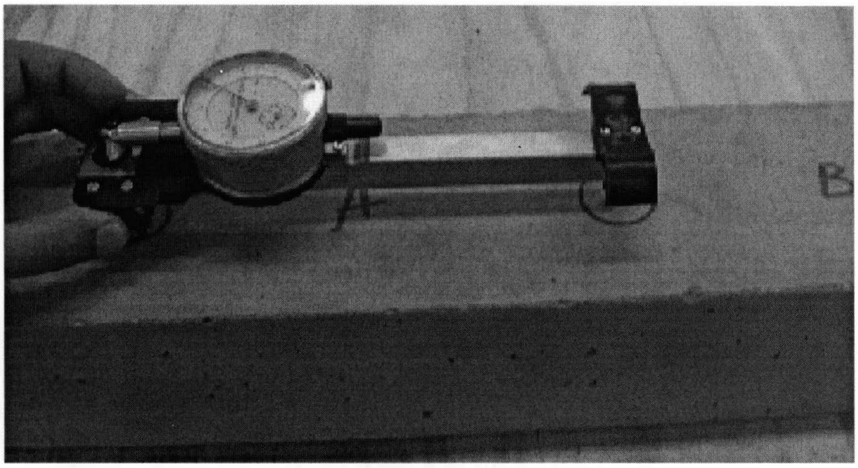


Figure 39: Measuring of Shrinkage Strain at Certain Days

Table 22: Shrinkage Strain of Recycled Aggregate Concrete

| Age of concrete under monitor (days) | Shrinkage strain (micro strain) | | | | |
|---|---|---|---|---|---|
| | Sample1 | Sample2 | Sample3 | Sample4 | ACI-209 predicted strain |
| 1 | 83 | 77 | 79 | 74 | 23 |
| 2 | 115 | 112 | 102 | 96 | 46 |
| 3 | 148 | 146 | 131 | 127 | 67 |
| 4 | 174 | 171 | 168 | 161 | 87 |
| 5 | 198 | 193 | 187 | 183 | 106 |
| 7 | 223 | 219 | 212 | 194 | 141 |
| 10 | 265 | 261 | 247 | 235 | 188 |
| 14 | 303 | 292 | 286 | 278 | 242 |
| 18 | 324 | 312 | 318 | 307 | 287 |
| 26 | 372 | 371 | 362 | 374 | 361 |
| 33 | 390 | 388 | 382 | 392 | 410 |
| 40 | 411 | 409 | 405 | 412 | 451 |
| 47 | 428 | 427 | 422 | 431 | 484 |
| 54 | 435 | 432 | 429 | 437 | 520 |

As the shrinkage was noted to be very small, all the strain values were taken in micro strain ($10^6$).

The shrinkage values for all the samples are plotted with time and are shown in Figure 40.

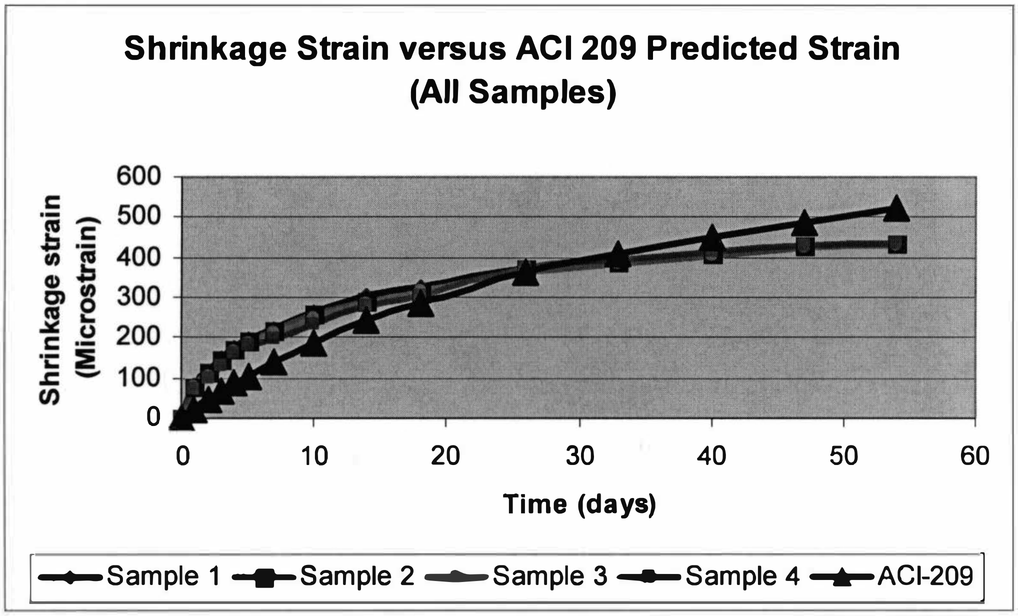



Figure 40: Shrinkage Strain for Recycled Aggregate Concrete versus ACI-209

Figure 40 shows that all the samples showed higher strain than the ACI predicted strain up to certain days but later on these values are under the predicted curve.

4.4.6 Resistance to Rapid Freezing and Thawing

This test is used to determine the resistance of concrete specimens to rapidly repeated cycles of freezing and thawing in the laboratory. Generally, this test is carried out in two different ways. One of the procedures is freezing and thawing in water while in the other one, specimens are subjected to rapid freezing in water and thawing in air. Both procedures are intended for use in determining the effects of variations in the properties and conditioning of concrete on its resistance to the repeated freezing and thawing cycles [56].

For this study the method of repeated freezing and thawing cycles in water was used. All the concrete samples of size 3"x 4"x16" were soaked in water tank for 14 days. Eight of the samples were placed in the machine while remaining chambers were filled by samples of the other research study. Concrete samples placed in the machine are shown Figure 41.

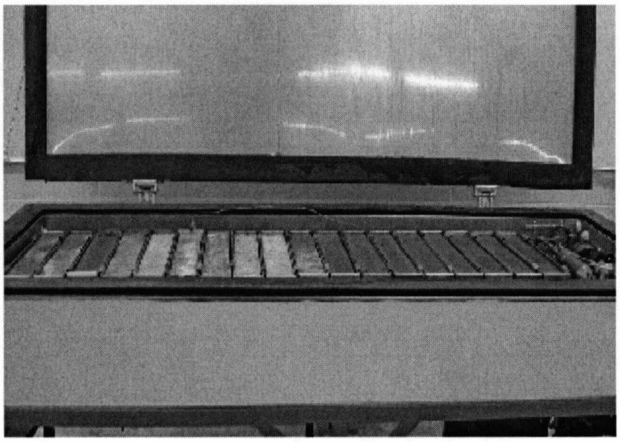


Figure 41: Concrete Samples in the Machine

According to the specifications of ASTM C 666-97 and AASHTO 161-93, the machine was set to make cycles in between 0 $^0$F and 40 $^0$F. For maintaining the same conditions, the temperatures of the concrete samples were brought to the range of 40 $^0$F, before they were kept in the machine. At this stage the initial readings of transverse frequency, dimensions and weights of all the samples were noted and the samples were kept in the thawing water at the beginning of the thawing phase of the cycle. This procedure was adopted every time during the intermediate readings. The intervals of the intermediate readings were in between 27 and 36 cycles. These cycles were noted on the graph of the machine, which is shown in Figure 42. The curve running from the circumference to the centre of the graph shows freezing of the samples while the curve running opposite to that, indicates thawing of the specimens.

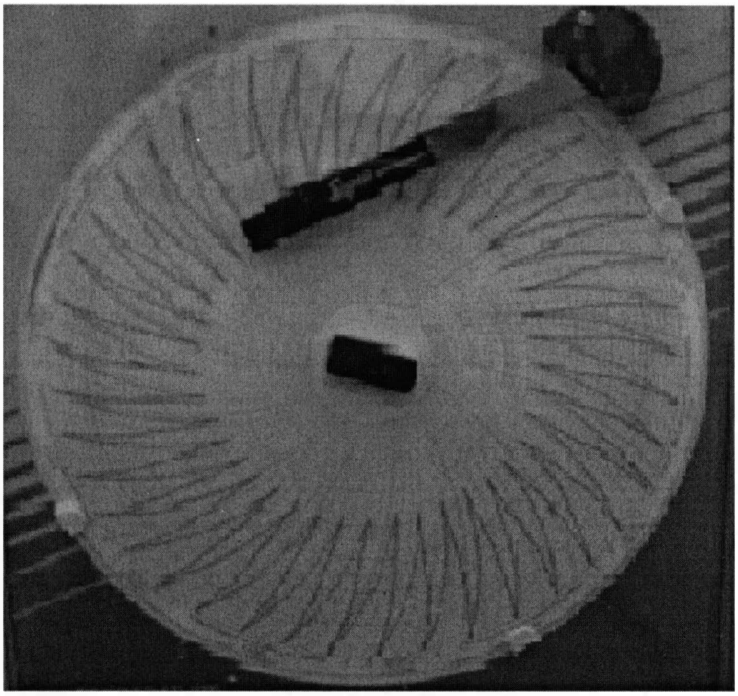


Figure 42: Graphical Representation of Freezing and Thawing Cycles

During monitoring of the samples at different intervals, no significant changes were noted in the concrete samples till 94 repeated cycles of freezing and thawing. After this stage, crumbling of the samples was started which were damaging specimens, severely. This process of crumbling and damaging of samples kept continue till 156 repeated cycles of freeze and thaw.

No significant changes were noted in the early stages of up to 124 cycles. But after that during the phase of cycles in between 156 and 222, the samples were noted loosing bond in between the ingredients. During monitoring at the end of 222 cycles it was easy to distinguish between coarse and fine aggregates in the samples. This segregation of aggregates got more devastated at the end of the next set of 30 cycles when 4 of the 8 samples were crumbled into pieces after 252 cycles. The remaining 4 samples were in the condition that could get crumbled anytime. It was even difficult to find the transverse frequencies of these samples when they lost much of the weights as compared to their initial weights. Rest of the 4 samples also got crumbled when they were inspected at the end of 282 cycles.

Crumbling of samples at initial and severe stages is shown in Figure 43 and Figure 44.

Figure 43: Initial Crumbling

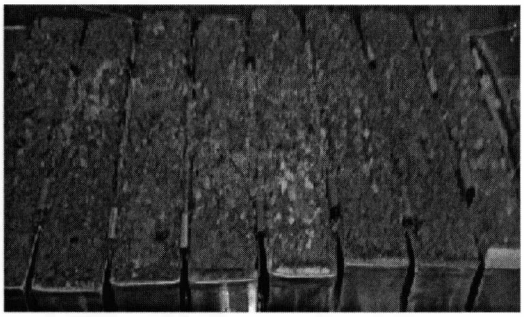
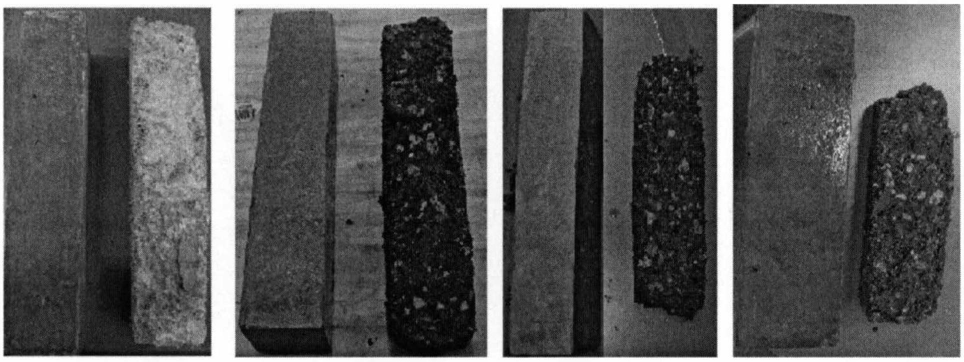


Figure 44: Severe Crumbling

Concrete samples before and after certain cycles are shown in Figure 45.



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

Figure 45: Concrete Samples after Certain Cycles (a): 94 cycles, (b):156 cycles (c): 222 cycles and (d):252 cycles

During monitoring of the concrete specimens, changes in weight, dimensions and transverse frequencies were noted.

Changes in frequencies were uniform in the earlier stages but after exposure to severe freezing and thawing cycles when samples started getting deteriorating, readings also started getting fluctuating. Weights of the samples also started getting affected in the later stages of the test. Values of relative dynamic modulus of elasticity, percent changes in weight and durability factors of all the samples are calculated using the following ASTM C 666- 97 formulae and are shown in Table 23 and Table 24 respectively.

- Relative Dynamic Modulus of Elasticity [56]

$P_c = (n_1{}^2 / n^2) \times 100$

Where:

$P_c$ = relative dynamic modulus of elasticity, after c cycles of freezing and thawing (percent)

n = fundamental transverse frequency at 0 cycles of freezing and thawing

$n_1$ = fundamental transverse frequency after c cycles of freezing and thawing

- Durability Factor [56]

DF = PN / M

Where:

DF = durability factor

P = relative dynamic modulus of elasticity at n cycles (percent)

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less, and

M = specified number of cycles at which exposure is to be terminated

- Percent Changes in Weight

WT = (present weight) / (initial weight) x 100

Table 23: Relative Dynamic Modulus of Elasticity at Different Cycles

| Cycles of freeze and thaw | Concrete specimens with relative dynamic modulus of elasticity (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 30 | 95.2 | 94.4 | 97.2 | 100.2 | 91 | 101.5 | 92.5 | 102.1 |
| 62 | 91.5 | 91.6 | 102.2 | 94.1 | 85 | 90.5 | 84.8 | 89.8 |
| 94 | 84.7 | 101.1 | 97.5 | 95.6 | 75.1 | 89.2 | 87.4 | 95 |
| 124 | 92.1 | 95.3 | 86.8 | 81 | 66.9 | 96.5 | 93.1 | 91.5 |
| 156 | 95.1 | 82.8 | 85 | 83 | 78.7 | 93.6 | 77 | 102.8 |
| 186 | 77 | 91.5 | 76 | 77.8 | 86 | 94.5 | 72.9 | 93.1 |
| 222 | 83.9 | 90 | 80 | 85.8 | 86.7 | 77 | 73.9 | 87.1 |
| 252 | 75.1 | 88.2 | 79.2 | 68.5 | 74.8 | ----- | ----- | ------ |
| 288 | ----- | ------ | ----- | ------ | ------ | ------ | ----- | ----- |
| 312 | ----- | ------ | ----- | ------ | ------ | ------ | ----- | ----- |

Table 24: Percent Changes in Weights and Durability Factors of the Samples at Certain Cycles

| Cycles of freeze and thaw | Percent changes in weight and durability factors of the concrete samples at certain cycles | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | |
| | DF | WT (%) | DF | WT (%) | DF | WT (%) | DF | WT (%) | DF | WT (%) | DF | WT (%) | DF | WT (%) | DF | WT (%) |
| 30 | 89.23 | +0.23 | 88.5 | +0.23 | 91.13 | +0.35 | 93.94 | +0.35 | 85.31 | +0.71 | 95.16 | +0.58 | 86.72 | +0.71 | 95.72 | +0.87 |
| 62 | 88.61 | +0.52 | 88.74 | +0.35 | 99.0 | +0.65 | 91.16 | +0.69 | 82.34 | +0.98 | 87.67 | +0.69 | 82.15 | +0.93 | 87.0 | +0.98 |
| 94 | 82.94 | +0.81 | 99.0 | +0.57 | 95.47 | +1.18 | 93.61 | +0.92 | 73.54 | +1.1 | 87.34 | +1.32 | 85.58 | +1.8 | 93.02 | +1.2 |
| 124 | 89.13 | +0.93 | 92.3 | +0.81 | 94.09 | +1.31 | 78.47 | -0.23 | 64.81 | +0.17 | 93.48 | +0.17 | 90.2 | +2.1 | 88.64 | +1.27 |
| 156 | 92.72 | +0.99 | 80.73 | +0.06 | 82.88 | +0.12 | 80.93 | -0.46 | 76.73 | -1.72 | 91.26 | -0.12 | 75.08 | +0.75 | 100.2 | +0.52 |
| 186 | 74.59 | -0.23 | 88.64 | -0.35 | 73.63 | -0.18 | 75.37 | -4.11 | 83.31 | -6.61 | 81.86 | -0.58 | 70.62 | -0.29 | 90.19 | -0.75 |
| 222 | 83.15 | -2.38 | 89.2 | -2.31 | 79.38 | -16.0 | 85.03 | -46.1 | 85.93 | -49.1 | 76.31 | -6.73 | 73.24 | -4.1 | 86.32 | -6.42 |
| 252 | 74.52 | -22.8 | 86.82 | -49.3 | 77.96 | -32.1 | 67.43 | ---- | 73.63 | ----- | ------ | ----- | ------ | ----- | ----- | ----- |
| 288 | ------ | ----- | ------ | ----- | ------ | ----- | ------ | ---- | ----- | ----- | ------ | ----- | ------ | ----- | ----- | ----- |
| 312 | ------ | ----- | ------ | ----- | ------ | ----- | ------ | ---- | ----- | ----- | ------ | ----- | ------ | ----- | ----- | ----- |

In Table 24, DF is durability factor and WT is change in the weight of the sample at respective cycles of freezing and thawing. The positive sign (+) with the weight shows increase and the negative sign (-) indicates loss in the weight of the sample.

## 4.5 Chapter Summary

If mixed and cured properly, compressive strength of concrete containing recycled aggregate develops in the same way and up to the same value as other concretes. The values found in this phase are comparable to other concretes.

The beams cured and tested for flexural strengths gave good and satisfactory results. The values were comparable to those found in literature search and other conventional concretes.

The only problem associated with recycled aggregate, noted during this study was its high tendency towards drying shrinkage. When the values of shrinkage were compared to ACI predicted values, they were higher earlier but came under the limits of the ACI values after certain time.

The concrete specimens were found to be durable during their exposure to resistance against rapid freezing and thawing cycles. But after certain cycles, they started crumbling and eventually lost the bonds. At the end of the tests all the samples were found in pieces.

The properties evaluated during this phase of study are summarized in Table 25.

Table 25: Summary of Evaluation of Mechanical Properties

| Property | Behavior in recycled aggregate concrete | Comparisons with literature and conventional concrete |
|---|---|---|
| Compressive strength | It is in the desirable and designed limits | 28-day strength for 50% recycled aggregate concrete is 6280 psi. This value up to 6800 psi for conventional concrete |
| Modulus of elasticity | Comparable to the values found in literature | 28-day modulus of elasticity for 50% recycled aggregate is $4305 \times 10^3$ psi. This value is up to $4420 \times 10^3$ psi found in literature and $4566 \times 10^3$ psi for the same concrete according to ACI equation. |
| Flexural strength | Comparable to other concretes | 28-day modulus of rupture value for 50% recycled aggregate is up to 793 psi which is comparable to the value of 653 psi for 75% recycled aggregate found in literature |
| Drying shrinkage | High tendency in the early stages | High shrinkage strain compared to ACI -209 predicted strains. But this value is lower after 33 days than the ACI limits. |
| Rapid freezing and thawing | Satisfactory results in the earlier stages | Good resistance up to 250 cycles of rapid freeze and thawing. Later on segregation of aggregates occurred. No data found for this test of recycled aggregate in literature |

The results summarized in Table 25 make the picture clear that the properties of recycled aggregate concrete evaluated during this phase and their comparison with other results shows that this concrete is capable to be used in structures under high loads and are exposed to varying environmental conditions though some adjustments are required during the mixing so that problems concerned with shrinkage are solved.

# CHAPTER 5

# BENEFIT-COST ANALYSIS

## 5.1 Introduction

Quality and costs are essential parameters for any construction project. The behavior of the construction materials are therefore tested within these two parameters.

During optimization, evaluation for mechanical properties and other laboratories experiments, recycled aggregate proved to be of good quality. It has sufficient strength and potential of withstanding in bond with other concrete materials for enough time.

In this phase of cost analysis, unit production cost and benefit to cost ratios are determined and the values were compared with virgin aggregate for same capacity.

## 5.2 Cost Parameters

Several cost parameters such as; equipment, land, tipping, labor and transportation, from the perspective of their cost analysis for both recycled and virgin aggregates are discussed in detail.

Analyses are based on the current and actual values and costs in the areas of southwest Michigan that are obtained during site visits.

### 5.2.1 Cost of Equipment

Equipments are the essential part of any businesses. Likewise, both recycling and virgin facilities also require acquiring recycling and crushing equipments. The most essential one of them is the recycling and crushing machines.

Based on their annual capacities, these equipments are categorized in small, medium and large sizes. Their purchasing price, estimated maintenance and operating (m/o) costs/year and their comparison with virgin aggregate equipment having the same capacities and maintenance and operating costs are shown in Table 26.

The operating costs of the machines include operator and helper cost, fuel and power cost, lubrication and other essentials of the machine costs.

Comparing purchasing costs of machines for recycling aggregates to those of virgin aggregates shows that initial costs to establish a recycling facility is higher. Due to higher purchasing costs and type of operations, like, crushing of demolished debris from different sources, its maintenance cost is higher too.

Table 26: Purchasing and Maintenance Costs of Machines

| Size of the equipment | Capacity (tons/yr.) | Recycled aggregate | | Virgin aggregate | |
|---|---|---|---|---|---|
| | | Cost of machine ($) | Maintenance and operating cost ($/yr.) | Cost of machine ($) | Maintenance and operating cost ($/yr.) |
| Small | 110,000 | 500,000 | 50,000 | 250,000 | 25,000 |
| Medium | 253,000 | 600,000 | 60,000 | 350,000 | 35,000 |
| Large | 312,000 | 750,000 | 75,000 | 500,000 | 50,000 |

### 5.2.2 Cost of Land

After purchasing equipments the next essential step in every business is to acquire land to operate those equipments. It is also obvious that land requirements will get increase with the size and capacity of the machine. It requires about 5 acres land to establish and run a recycling facility of smaller capacity. Land requirements increase to 10 acres and 15 acres when a recycling facility of medium or large capacity is desired to be established [9].

Selection of land to establish a business is a challenging job. In case of recycling facility, if it is desired to start it in the rural area where land price is cheap as compared to urban areas, it will lose most of the customers who need recycled aggregate in urban area because of higher transport charges. That is why most of the businesses try to get land on lease and establish business as near as possible to area where business is on rise.

For the same capacity, land requirement remains same for recycled and virgin aggregate. Land costs for all three types of recycling machines with lease rate both in urban and rural areas of southwest Michigan counties are shown in Table 27.

Table 27: Cost of Land and Leasing Prices in Southwest Michigan

| Size of equipment | Land required (acre) | Urban areas | | | Rural areas | | |
|---|---|---|---|---|---|---|---|
| | | Purchasing cost/acre ($) | Lease rate (acre/yr) ($) | Total lease cost ($) | Purchasing cost/acre ($) | Lease rate (acre/yr) ($) | Total lease cost ($) |
| Small | 5 | 2,00,000 | 20,000 | 1,00,000 | 22,000 | 22,00 | 11,000 |
| Medium | 10 | 2,00,000 | 20,000 | 2,00,000 | 22,000 | 22,00 | 22,000 |
| Large | 15 | 2,00,000 | 20,000 | 3,00,000 | 22,000 | 22,00 | 33,000 |

Table 27 shows that it makes a big difference if the land is purchased or acquired on lease and whether in rural or urban area.

### 5.2.3 Unit Value

The demand of a good quality product always increases in the marketplace. The same rule applies in the aggregate industry, where quality plays an important role, because recycled aggregate is available in different grades. For example, the lowest graded quality of recycled aggregate, which contains a large amount of fines and dust that is used mostly in backfill, costs about $1/ton. In contrast, if the same aggregate is in a very fine shape after screening, washing and spraying, is available at $15/ton as a highly specialized landscape rock [9].

Depending on the crushing facility, source and availability of the aggregate and intended use, the unit value of recycled aggregate varies from place to place.

### 5.2.4 Tipping Fees

Tipping fees is the amount, landfills charge when their land and facility is used to process the materials [9]. Depending upon the location and type of facility, tipping fees vary in different locations. In areas where space for landfill is limited, this rate is high which is mainly aimed to discourage the dumping and consequently encourage recycling of demolished debris. On the other hand where space for landfill is abundant, this rate is comparatively low.

In most of the counties in southwest Michigan tipping fee for dumping demolition debris are in $15 and $18 per ton range, while tipping charges for recycling aggregate are in the range of $8 to $10 a ton.

As it is less costly to recycle aggregate as compared to dumping it, the trend of recycling aggregate is on rise. It will also be more convenient to establish a mobile recycling plant and reuse the material instead of taking it to landfill site and dump it. It will increase the cost when hauling cost is added up.

### 5.2.5 Labor Charges

In every construction project, labor charges are one of the most expensive parts. Therefore reduction in cost of labor will ultimately reduce the cost of the project.

The number of labors required to run a recycling facility is very low as compared to the number needed to operate a crushing plant for natural rock. It is estimated that a typical recycling facility of medium capacity requires about 9 to 12 persons [9], to achieve its daily production as compared to about 14 to 16 persons for crushing plant of natural aggregate. If it is required to use a mobile facility the labor requirement may increase, because some extra people are needed to set up the facility when it is relocated. This factor is however covered by eliminating the hauling costs, when mobile crushing plant is used [9].

Material and transportation costs are considered for the facilities that are intended to recycle or crush their aggregates. For recycling facility, this material is available at a cost of $1/ton and in most of the cases facility is established very near to the source material. It is estimated to be in the area of 1 km radius. For virgin aggregates the big rocks are estimated in the range of about $2 to $4/ ton with the source in the same range.

### 5.2.6 Transportation Cost

Depending on the distances from demolished structures, recycling plant, crushing plant, landfill site and construction site, transportation cost can play a pivotal role. It is therefore judged upon the cost-effective factor to decide whether to recycle or dump the aggregate. If it costs more to recycle, a construction manager's point of view will be to dump the debris and use the natural aggregate.

Transportation charges also change from state to state. It costs up to $2.00/ton/km in southwest Michigan region.

All the cost parameters that are explained above and are to be considering during benefit to cost analysis are summarized in Table 28.

Table 28: Description of Estimated Cost Parameters in Southwest Michigan

| Cost Parameters | Description | Effects |
|---|---|---|
| Equipment with m/o costs | The main crushing or recycling machine | Initial and maintenance cost for recycling is high |
| Cost of land | Area to establish a facility | Same for both the options |
| Tipping fee | The amount landfills charge | Amount is higher when debris are dumped in than to recycle them |
| Labor charges | Manpower to process the facility | Recycling machines require less labor than the crushing machine |
| Transportation costs | Amount require to transport demolished debris from demolished site to recycling plant or landfill site | This rate remains same for both aggregates |

## 5.3 Benefit to Cost Analysis

In light of studies from all over the United States, facts and figures are focused on southwest Michigan region. For the calculation and comparison of cost to benefit analysis of recycling and crushing facilities some assumptions are made:

- Analysis are based on the 10-year performance of the machines
- Medium size machines are considered for the evaluation of benefit to cost and unit production prices for both recycled and virgin aggregates
- The capacities of the machines, considered for study are 80% of their designed capacity per year
- All the environmental conditions are normal
- For labor cost the schedule of 40 hrs/week is considered
- Land is obtained on lease in urban area
- 6% compound rate is considered which is the usual rate in the area

Keeping in view all the parameters discussed above, values obtained and assumptions made, cost to benefit ratios and unit production cost are find out for 4 different alternatives:

- Crushing facility for virgin aggregates
- Recycling facility which runs on the revenues of tipping fees only
- Recycling facility which runs half on tipping fee and half on the sale of recycled aggregates of its own
- Recycling facility which runs on the 100% sales of the aggregates recycled by itself and which do not offer any services for tipping fee

All these values are calculated on actual costs and are shown in the Tables 29, 30, 31 and 32.

Apart for the initial cost of the equipment, which is the purchasing price of the machine, rest of the costs and revenue values get change at a compound rate of 6% with every passing year. For calculations of all the costs, these values are converted to year zero (Pw), which is calculated using the formula

$$Pw = \Sigma P = \Sigma F (1+i) ^\wedge (-n)$$

In the Tables, "n" shows number of years, "i" is the compound rate, "F" is the cost/yr and calculated "Pw" is the present worth value of the respective cost parameter at year zero.

Table 29: Present Worth Value (Pw) of Cost Factors for Virgin Aggregate Facility

| Cost Parameters | | Maintenance & operation | | Labor | | Lease | | Material & transport | | Sales Revenue | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| n | i | F | P | F | P | F | P | F | P | F | P |
| 0 | | | | | | | | | | | |
| 1 | 6% | 35,000 | 33,019 | 307,200 | 289,811 | 200,000 | 188,679 | 809,600 | 763,774 | 2,024,000 | 1,909,434 |
| 2 | 6% | 35,000 | 31,150 | 307,200 | 273,407 | 200,000 | 177,999 | 809,600 | 720,541 | 2,024,000 | 1,801,353 |
| 3 | 6% | 35,000 | 29,387 | 307,200 | 257,931 | 200,000 | 167,924 | 809,600 | 679,756 | 2,024,000 | 1,699,389 |
| 4 | 6% | 35,000 | 27,723 | 307,200 | 243,331 | 200,000 | 158,419 | 809,600 | 641,279 | 2,024,000 | 1,603,198 |
| 5 | 6% | 35,000 | 26,154 | 307,200 | 229,558 | 200,000 | 149,452 | 809,600 | 604,980 | 2,024,000 | 1,512,451 |
| 6 | 6% | 35,000 | 24,674 | 307,200 | 216,564 | 200,000 | 140,992 | 809,600 | 570,736 | 2,02,4000 | 1,426,840 |
| 7 | 6% | 35,000 | 23,277 | 307,200 | 204,306 | 200,000 | 133,011 | 809,600 | 538,430 | 2,024,000 | 1,346,076 |
| 8 | 6% | 35,000 | 21,959 | 307,200 | 192,741 | 200,000 | 125,482 | 809,600 | 507,953 | 2,024,000 | 1,269,883 |
| 9 | 6% | 35,000 | 20,716 | 307,200 | 181,831 | 200,000 | 118,380 | 809,600 | 479,201 | 2,024,000 | 1,198,002 |
| 10 | 6% | 35,000 | 19,544 | 307,200 | 171,539 | 200,000 | 111,679 | 809,600 | 452,076 | 2,024,000 | 1,130,191 |
| Present worth value at zero year = Pw ($) | | | 257,603 | | 2,261,019 | | 1,472,017 | | 5,958,726 | | 14,896,816 |

Table 30: Present Worth Value (Pw) of Cost Factors for Recycled Aggregate Facility with 100% Tipping Fee Revenue

| Cost Parameters | | Maintenance & operation | | Labor | | Lease | | Tipping fee Revenue | |
|---|---|---|---|---|---|---|---|---|---|
| n | i | F | P | F | P | F | P | F | P |
| 0 | | | | | | | | | |
| 1 | 6% | 60,000 | 56,604 | 230,400 | 217,358 | 200,000 | 188,679 | 2,024,000 | 1,909,434 |
| 2 | 6% | 60,000 | 53,400 | 230,400 | 205,055 | 200,000 | 177,999 | 2,024,000 | 1,801,353 |
| 3 | 6% | 60,000 | 50,377 | 230,400 | 193,448 | 200,000 | 167,924 | 2,024,000 | 1,699,389 |
| 4 | 6% | 60,000 | 47,526 | 230,400 | 182,498 | 200,000 | 158,419 | 2,024,000 | 1,603,198 |
| 5 | 6% | 60,000 | 44,835 | 230,400 | 172,168 | 200,000 | 149,452 | 2,024,000 | 1,512,451 |
| 6 | 6% | 60,000 | 42,298 | 230,400 | 162,423 | 200,000 | 140,992 | 2,024,000 | 1,426,840 |
| 7 | 6% | 60,000 | 39,903 | 230,400 | 153,229 | 200,000 | 133,011 | 2,024,000 | 1,346,076 |
| 8 | 6% | 60,000 | 37,645 | 230,400 | 144,556 | 200,000 | 125,482 | 2,024,000 | 1,269,883 |
| 9 | 6% | 60,000 | 35,514 | 230,400 | 136,373 | 200,000 | 118,380 | 2,024,000 | 1,198,002 |
| 10 | 6% | 60,000 | 33,504 | 230,400 | 128,654 | 200,000 | 111,679 | 2,024,000 | 1,130,191 |
| Present worth value at zero year = Pw ($) | | | 441,605 | | 1,695,764 | | 1,472,017 | | 14,896,816 |

Table 31: Present Worth Value (Pw) of Cost Factors for Recycled Aggregate with 50% Revenue from Tipping Fee

| Cost Parameters | | Maintenance & operation | | Labor | | Lease | | Material & transport | | Tipping fee revenue | | Sales Revenue | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| n | i | F | P | F | P | F | P | F | P | F | P | F | P |
| 0 | | | | | | | | | | | | | |
| 1 | 6% | 60,000 | 56,604 | 230,400 | 217,358 | 200,000 | 188,679 | 303,600 | 286,415 | 1,012,000 | 954,716 | 404,800 | 381,886 |
| 2 | 6% | 60,000 | 53,400 | 230,400 | 205,055 | 200,000 | 177,999 | 303,600 | 270,202 | 1,012,000 | 900,676 | 404,800 | 360,270 |
| 3 | 6% | 60,000 | 50,377 | 230,400 | 193,448 | 200,000 | 167,923 | 303,600 | 254,908 | 1,012,000 | 849,694 | 404,800 | 339,877 |
| 4 | 6% | 60,000 | 47,526 | 230,400 | 182,498 | 200,000 | 158,418 | 303,600 | 240,479 | 1,012,000 | 801,598 | 404,800 | 320,639 |
| 5 | 6% | 60,000 | 44,835 | 230,400 | 172,168 | 200,000 | 149,451 | 303,600 | 226,867 | 1,012,000 | 756,225 | 404,800 | 302,490 |
| 6 | 6% | 60,000 | 42,298 | 230,400 | 162,422 | 200,000 | 140,992 | 303,600 | 214,026 | 1,012,000 | 713,420 | 404,800 | 285,368 |
| 7 | 6% | 60,000 | 39,903 | 230,400 | 153,229 | 200,000 | 133,011 | 303,600 | 201,911 | 1,012,000 | 673,037 | 404,800 | 269,215 |
| 8 | 6% | 60,000 | 37,645 | 230,400 | 144,555 | 200,000 | 125,482 | 303,600 | 190,482 | 1,012,000 | 634,941 | 404,800 | 253,976 |
| 9 | 6% | 60,000 | 35,514 | 230,400 | 136,373 | 200,000 | 118,379 | 303,600 | 179,700 | 1,012,000 | 599,001 | 404,800 | 239,600 |
| 10 | 6% | 60,000 | 33,504 | 230,400 | 128,654 | 200,000 | 111,678 | 303,600 | 169,528 | 1,012,000 | 565,095 | 404,800 | 226,038 |
| Present worth value at zero year = Pw ($) | | | 441,605 | | 1,695,764 | | 1,472,017 | | 2,234,522 | | 7,448,408 | | 2,979,363 |

Table 32: Present Worth Value (Pw) of Cost Factors for Recycled Aggregate with 100% Sales Revenue

| Cost Parameters | | Maintenance & operation | | Labor | | Lease | | Material & transport | | Sales Revenue | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| n | i | F | P | F | P | F | P | F | P | F | P |
| 0 | | | | | | | | | | | |
| 1 | 6% | 60,000 | 56,604 | 230,401 | 217,359 | 200,000 | 188,679 | 60,720 | 57,283 | 809,600 | 763,773 |
| 2 | 6% | 60,000 | 53,400 | 230,401 | 205,056 | 200,000 | 177,999 | 60,720 | 54,040 | 809,600 | 720,541 |
| 3 | 6% | 60,000 | 50,377 | 230,401 | 193,450 | 200,000 | 167,923 | 60,720 | 50,981 | 809,600 | 679,755 |
| 4 | 6% | 60,000 | 47,526 | 230,401 | 182,501 | 200,000 | 158,418 | 60,720 | 48,095 | 809,600 | 641,279 |
| 5 | 6% | 60,000 | 44,835 | 230,401 | 172,172 | 200,000 | 149,451 | 60,720 | 45,373 | 809,600 | 604,980 |
| 6 | 6% | 60,000 | 42,298 | 230,401 | 162,427 | 200,000 | 140,992 | 60,720 | 42,805 | 809,600 | 570,736 |
| 7 | 6% | 60,000 | 39,903 | 230,401 | 153,233 | 200,000 | 133,011 | 60,720 | 40,382 | 809,600 | 538,430 |
| 8 | 6% | 60,000 | 37,645 | 230,401 | 144,560 | 200,000 | 125,482 | 60,720 | 38,096 | 809,600 | 507,953 |
| 9 | 6% | 60,000 | 35,514 | 230,401 | 136,378 | 200,000 | 118,379 | 60,720 | 35,940 | 809,600 | 479,200 |
| 10 | 6% | 60,000 | 33,504 | 230,401 | 128,654 | 200,000 | 111,678 | 60,720 | 33,905 | 809,600 | 452,076 |
| Present worth value at zero year = Pw ($) | | | 441,605 | | 1,695,795 | | 1,472,017 | | 446,904 | | 5,958,726 |

## 5.4 Chapter Summary

The values of cost to benefit ratios and unit production costs for all the 4 alternatives are calculated using the following formulae.

Cost/benefit ratio = $\Sigma$ Pw $_{revenue}$ / $\Sigma$ Pw $_{cost}$

Unit production cost = (Sum of all the costs of a facility) / (capacity of the machine for the designed period)

These values are shown with the current sales price of the respective material in the areas that is under consideration for this study in Table 33.

Table 33: Summary of B/C and Unit Production Cost for All the Alternatives

| Type of facility | Current sale price ($/ton) | Unit production cost ($) | B/C ratio |
|---|---|---|---|
| Recycling with 100% tipping fees revenue | 4.0 | 2.1 | 3.45 |
| Recycling with 100% sales revenue | 4.0 | 2.3 | 1.28 |
| Recycling with 50% tipping revenue | | 3.2 | 1.62 |
| Virgin aggregate | 10.0 | 5.1 | 1.45 |

After applying these two essential checks of engineering economics (benefit to cost ratio and unit production cost) and comparing the values of the summary table in themselves, it is now obvious that it is feasible to establish recycling facility, because all the values are over 1, which means that costs of all these facilities are lower than benefit.

As the values in the summary table are listed in categorical order therefore having available all the 4 alternatives the first one listed should be preferred.

Having the lowest unit production cost and highest cost to benefit ratio, the recycling facility with 100% tipping revenue is the most feasible and favorable for business point of view. But if the circumstances do not allow this facility, like lack of customers, the next alternative should be the second in the summary table, which is the recycling facility which runs on revenue of the total sales of the product recycled by its own.

In the areas where the first two choices are not possible by anyways, the third alternative is the facility which is the combination of the first twos. It runs on the 50% sales of own recycled products with 50% revenue from the tipping fee. The analysis shows that the virgin aggregates crushing plants should be the last option and should be adopted when the establishment of all other facilities considered in this study, is not possible.

# CHAPTER 6

# GUIDELINES FOR USING RECYCLED AGGREGATE CONCRETE

## 6.1 Introduction

During this research study, recycled aggregate concrete is evaluated while considering several parameters of a construction process, such as optimization, detailed mechanical properties and benefit to cost analysis. During the whole process, it was noted that recycled aggregate has some merits and demerits.

This research study has some limitations as a whole and at the end of every phase, respective results, conclusions, advantages and drawbacks are achieved. In this chapter all these points are discussed in details. Though recycled aggregate proved to be of satisfactory performance both quality and cost wise, yet its further enhancement will improve the quality of the projects, it is intended to be used in. The observations at different stages and alterations or adjustments for further enhancement of the performance, at several stages are combined to develop the guidelines for using recycled aggregate concrete in different construction projects.

It is highly recommended to follow these guidelines while using recycled aggregate in any construction projects. They are explained below:

1. Aggregates from demolished highways are much more prone to wear and tear as compared to the debris from buildings, bridges or other applications. Having option of source of aggregate, for better performance, prefer to use recycled aggregates from the debris of buildings.

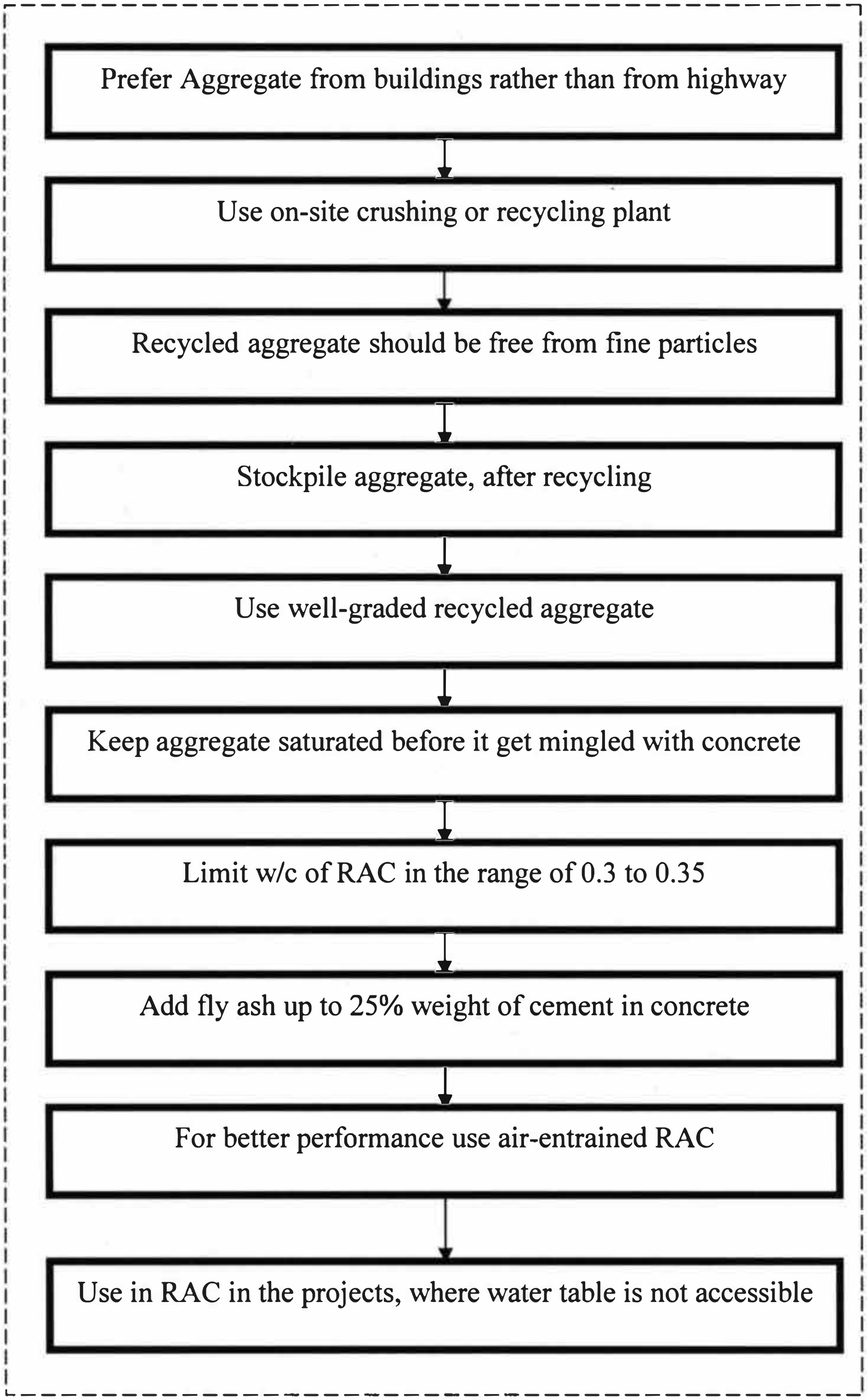
2. To reduce the cost of the process, on-site mobile crushing or recycling machines should be used. These are simple to operate with less manpower and do not require skilled labor.
3. Due to the conventional methods of recycling aggregates, the process results in the formation of huge amount of fine dust material. These materials do not have any effect if recycled aggregate is used in areas where concrete mix designs or water requirements are not point of concerns. But since recycled aggregate is a high water requirement material, the addition of these fine dust materials will further increase this requirement which can affect setting time, workability, strength and other parameters of the concrete. It is therefore required to remove all these undesired fine dust material before using recycled aggregate in concrete. In worst case scenario washing material will remove most of the undesired particles.
4. Demolished debris from different projects and several methods of recycling may cause recycled aggregates blended with certain undesired substances. They can include glass, wood, bitumen, different sulfates, lead and plastics etc. Depending upon the jurisdictions, these elements should not exceed from the limits established by the responsible agencies. Stockpiling of recycled aggregate will help in the segregation and easy removal of fine particles and undesired substances.
5. Conduct the sieve analysis test for recycled aggregate in accordance of ASTM C 136 specifications. Furthermore, for better performance use aggregate of the gradation curve within the limits of ASTM C 136. The performance of the

concrete will be enhanced if recycled aggregate are used of the same grades as conventional aggregate or within the allowable limits of ASTM.

6. To overcome the high water absorption quality of recycled aggregate, which can affect mixing water, it should be kept saturated before introducing it to the concrete. Continue sprinkling water or any other form of keeping aggregates saturated, will solve this problem. It will also help in removing fine particles if free drainage system is provided.
7. To overcome the problems associated with high shrinkage, w/c of recycled aggregate concrete, should be in the limits of 0.3 and 0.35 (below 0.4). If cost of the project is not a point of concern, this problem can also be solved by the addition of water reducers.
8. Use 25% of fly ash by weight of cement used in concrete. Fly ash is very fine in nature and its cost is negligible as compare to cement. Furthermore, it does not affect the quality of concrete and reduces the cost.
9. If the target use of recycled aggregate concrete is in the area having varying weather conditions, its performance can further be improved if used as air entrained. This will help to overcome the problem of loosing bond and will enhance the performance of concrete under repeated cycles of freeze and thaw.
10. Recycling aggregate has a tendency of bleaching. The process causes the development of Mg and Ca when it reacts with water table. The use of recycled aggregate in construction projects, especially pavements, is therefore not suggested in the areas where water table has accessibility to get mingled with recycled aggregate.

The layout of guidelines for using recycled aggregate concrete is shown in Figure 46.

Figure 46: General Layout of Guidelines for Recycled Aggregate Concrete



# CHAPTER 7

# CONCLUSIONS AND RECOMMENDATIONS

## 7.1 Introduction

The improvement of infrastructure is getting extra attention in the United States and the rest of the world alike. One of the most important parts of the construction infrastructure in the US is its highways. Highways are under great wear and tear and are more susceptible to deterioration because of its frequent use; therefore it needs to be maintained on continuous basis.

Highway maintenance requires demolition and construction which produces wastes. At one end, these processes of maintenance, demolition and construction are essential for the infrastructure growth but on the other end they produce many wastes too, which is estimated to be about 200 millions tons per year [5] right now and is predicted to be climbing at a very high rate. This production of waste and its growth are creating certain problems. Dumping the waste in landfill sites, production of piles of construction debris, additional cost of transporting this waste to site and its effect on environment are some of the usual problems associated with this waste.

In order to avoid some of the problems associated with the construction and demolition debris the usual conventional method is to use it in low bearing structures such as a base coarse for parking lots, highways and filling material for retaining walls and other applications. This use of the demolished debris does not solve the problem completely because the debris is not used to the full. The other alternative therefore, is to recycle this waste, evaluate its properties and compare them with those of other aggregates to find out whether it is feasible to use it as a normal aggregate.

## 7.2 Conclusions

The laboratory work in this research study is sub-divided into three phases and respective conclusions were drawn in each phase.

### 7.2.1 Phase 1

The initial phase was the optimization of the concrete mix. Several trial concrete mixes were carried out in this phase in order to determine the optimum amount of conventional aggregate that can be substituted by recycled coarse aggregate, without affecting the essential properties of the concrete.

The study reached the following conclusions in this phase:

1. Sieve analysis curve for the recycled aggregate had some missing grades when it was compared with the gradation curve of conventional aggregate
2. For best results, it is important that recycled aggregate should be clear from dust, fine particles and other impurities like glass, bitumen and wood particles
3. Recycled aggregate is a high water absorption material. The aggregate used for tests was found to have water absorption of 6.5% comparing to 3.2% of the conventional aggregate
4. The specific gravity and moisture content of the recycled aggregate were found to be the same range as for other conventional aggregate. Its specific gravity was 2.27 and moisture content was 10%, compared to the values of 2.49 and 8% for the same properties of conventional aggregate
5. 50% recycled material by weight as coarse aggregate in concrete mix was found to be optimum amount. Workability and compressive strength were the evaluation criterion for the  selection of the optimum amount of recycled aggregate

6. Compressive strength of the concrete mix decreases with the increase in the proportion of recycled aggregate
7. The concrete mixes with different proportions of recycled aggregate were found to be of enough strength. Such as, the 28-day compressive strength of concrete with 50% recycled aggregate was 6400 psi. It is comparable to concrete mix with 100% conventional concrete, which was found to have compressive strength of 7550 psi
8. During compressive strength test recycled aggregate remained unbroken when the concrete specimen got fractured

### 7.2.2 Phase 2

The optimized concrete mix with 50% recycled aggregate was further investigated and evaluated for mechanical properties of concrete. These tests included compressive strength, flexural strength, modulus of elasticity, drying shrinkage and repeated cycles of freeze and thaw. Material testing was conducted in accordance with ASTM and AASHTO specifications. To observe the behavior of the concrete with recycled aggregate as a whole, the resulted values were compared to results found in literature.

The study came up with following conclusions in the phase of evaluation of mechanical properties:

1. The properties of recycled aggregate in concrete obtained in this phase of study are consistent and within the range of values found by other researchers
2. The values of compressive strength are well above the designed ones
3. The optimized concrete mix was found to be of enough strength under the application of axial compressive load. Compressive strength value of 28 days for the optimized mix, obtained was 6280 psi. This value was found to be in the range

of 4800 to 5500 psi by other researchers. For conventional aggregate concrete this value was found to be in the range of 6800 psi.

4. Recycled aggregate concrete performed well under flexural strength. Modulus of rupture value of the optimized mix for 28 days was found to be 793 psi. This value is comparable to the value of 653 psi, found by other researchers, though it is for the concrete mix with 75% recycled aggregate
5. The modulus of elasticity value of the optimized mix obtained, for 28 days was is the permissible range too. This value is $4305 \times 10^3$ psi. Other researchers found this value up to $4420 \times 10^3$
6. Drying shrinkage test revealed that recycled aggregate has a higher tendency towards shrinkage in the earlier stages. The concrete samples kept under observations for this property of concrete were found to gained higher shrinkage than the ACI predicted limits till the first 3 weeks. After that, the shrinkage of the samples came under the predicted values of ACI
7. Exposure of concrete samples with 50% recycled aggregate resisted well against the repeated freeze and thaw cycles up to 220 cycles. But later on they started loosing bonds in between the materials of the concrete and eventually crumbled into pieces at the end of 282 cycles
8. In this phase it was concluded that quality wise, recycled aggregate concrete has potential of sustaining high loads and can remain with no significant changes in shape, under varying environmental conditions

### 7.2.3 Phase 3

Once recycled aggregate showed satisfactory results in the extensive evaluation of the optimized concrete mixture, it was evaluated for cost analysis. During this phase the practical scenarios of the machines with same capacities were considered both for recycling the old and crushing the conventional aggregates. Also for recycling facilities further alternatives were evaluated. They were recycling facility with 100% tipping, with 50% tipping and with 100% normal sales revenues. Cost to benefit (C/B) ratios and unit production costs were calculated for all the alternatives.

During this phase the analysis resulted in the following conclusions:

1. The most beneficial in all the alternatives evaluated, is the recycling facility with 100% revenue from tipping fees. Its unit production cost and C/B are $2.1 and 3.45 respectively. These values were found to be $2.3 and 1.28 for 100% sales revenue and $3.2 and 1.62 for 50% tipping fees revenues facilities. For conventional aggregate crushing facility, these values are found to be $5.1 and 1.45 respectively.
2. The market of recycling aggregate depends on several factors and conditions such as support from government agencies, distances between demolition site, landfill site and construction sites, disposal and tipping fee structures, supply and production trends in the market, the current market rate and availability of conventional aggregate
3. It takes less labor to work on a recycling machine than to work on the conventional aggregate machine
4. The initial cost of recycling machine is much higher than the conventional crushing machine

5. Recycling of aggregate will help to reduce the amount of waste disposed in landfills and will also preserve natural resources and landscape
6. It was concluded in this phase that to have the lowest production cost but high C/B ratio than the conventional crushing facility, it is feasible to establish recycling facility.

## 7.3 Contributions and Limitations

Some of the main contributions of the author during this study are as follow:

1. To find out the optimum amount of recycled aggregate in the concrete with less affect on other mechanical properties of concrete
2. Findings about the behavior of recycled aggregate concrete in the repeated cycles of freeze and thaw
3. Calculations of unit production cost for different alternatives of recycling facilities
4. Comparison of cost to benefit ratios for recycling and conventional aggregate facilities

The limitations of this research study are as follow:

1. The results and analysis are limited to the recycled aggregate obtained from one source. This aggregate was obtained from a torn up portion of I-69 near Lansing
2. During the evaluation phase the results are limited to the concrete containing 50% recycled material as coarse aggregate
3. The limitations considered during benefit to cost analysis phase are:
    a. Medium sized recycling and crushing facility
    b. Ideal weather
    c. 10 years design period

d. 40 hours work schedule

e. 6% compound rate

## 7.4 Recommendations for Future Work

Based on the research study and conclusions drawn about recycled aggregate the following recommendations are proposed:

1. The scope of the study should be extended by evaluating the mechanical properties of the concrete with proportions of recycled aggregate other than 50%.
2. Recycled aggregate with fines and other impurities should not be used in the concrete mix for any load bearing structure. If it is possible or required, recycled aggregate should be sprinkled with water which will remove most of the dust and fine particles
3. The results from shrinkage analysis recommends that behavior of recycled aggregate concrete should be tested for creep analysis
4. It is also recommended to evaluate the performance of recycled aggregate concrete in reinforced structures. For further investigation of bond between rebars and concrete pull out test should be performed.

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