USE OF CONCRETE DEMOLITION WASTE AS AGGREGATES IN AREAS THAT HAVE SUFFERED DESTRUCTION

A Feasibility Study

S.A. Frondistou-Yannas, Assistant Professor of Civil Engineering, Principal Investigator

Herbert Tung S. Ng, Graduate Student, Research Assistant

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DISCLAIMER

ABSTRACT

Millions of tons of concrete debris are annually generated by natural disasters. For instance, the San Fernando Earthquake of 1971 generated 5 million tons of concrete debris. Disposal of such massive quantities of concrete waste poses a difficult problem. Moreover, during the reconstruction period significant demand usually develops for construction materials, with resulting material shortages and price inflation.

In the wake of a natural disaster, therefore, a sudden upsurge in supply of concrete debris coincides with a compelling demand for construction materials. Recycling of concrete debris as aggregate for new concrete suggests itself as an environmentally responsible mechanism for solution of the problem which is posed. In this report we examine the technical and economic aspects of such a solution.

Our findings suggest that such recycling of concrete debris is technologically feasible. Moreover, it is economically attractive provided that at least one million tons of concrete debris has been produced by the catastrophic event.

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TABLE OF CONTENTS

Page

Title Page 1
Disclaimer 2
Abstract 3
Acknowledgments 4
Table of Contents 5
List of Tables 7
List of Figures 9

Chapter 1: INTRODUCTION 10

Chapter 2: TECHNOLOGICAL FEASIBILITY OF CONCRETE RECYCLING 15
- 2.1 INTRODUCTION 15
- 2.2 EXPERIMENTAL PROCEDURE 18
  - 2.2.1 Materials 19
  - 2.2.2 Mixed Proportions 20
  - 2.2.3 Geometry, Curing and Testing of Specimens 20
- 2.3 RESULTS 21
- 2.4 DISCUSSION 23
- 2.5 CONCLUSIONS 24

Chapter 3: ASSESSMENT OF THE QUANTITIES OF CONCRETE DEBRIS PRODUCED IN AN EARTHQUAKE 26
- 3.1 METHOD FOR ESTIMATING THE QUANTITIES OF CONCRETE DEBRIS: AN OVERVIEW 26
- 3.2 AMOUNT OF CONCRETE PER SQUARE FOOT OF BUILDING SPACE THAT NEEDS REPLACEMENT IN A HEAVILY OR TOTALLY DAMAGED BUILDING 28
- 3.3 AMOUNT OF SQUARE FOOTAGE WHICH IS HEAVILY OR TOTALLY DAMAGED 29
- 3.4 TOTAL TONNAGE OF CONCRETE DEBRIS GENERATED 31
- 3.5 HIGHWAY DAMAGE ESTIMATION 32
- 3.6 CASE STUDY. THE SAN FERNANDO EARTHQUAKE OF 1971 32

Table of Contents - Continued

Page

3.6.1 Concrete Debris Generated from Building Damage 32
3.6.2 Concrete Debris Generated from Highway Damage 34
3.6.3 Total Amount of Concrete Debris Generated in the San Fernando Earthquake of 1971 35
3.7 SUMMARY AND CONCLUSIONS 35

Chapter 4: RECYCLING TECHNOLOGY 37
4.1 INTRODUCTION 37
4.2 DESIGN OF CONCRETE RECYCLING PLANTS 39
4.3 POTENTIAL OF NEW TECHNOLOGIES FOR THE RECYCLING PLANTS 42
4.4 THE SANITARY LANDFILL ADJACENT TO THE PLANT 43

Chapter 5: ECONOMIC FEASIBILITY OF CONCRETE RECYCLING 44
5.1 INITIAL INVESTMENT IN THE RECYCLING PLANTS AND SLF's 44
5.2 PRODUCTION COST ESTIMATE FOR THE RECYCLING PLANTS AT THE SLF SITES 46
5.3 ANNUAL INCOME STATEMENTS OF RECYCLING SYSTEMS 50
5.4 ATTRACTIVENESS OF INVESTING IN THE RECYCLING SYSTEMS 51
5.5 COMPARISON OF RECYCLED AGGREGATE CONCRETE AND NATURAL AGGREGATE CONCRETE 53
5.6 CONCLUSIONS ON THE ECONOMIC FEASIBILITY OF CONCRETE RECYCLING 54

Chapter 6: CONCLUSIONS 56

References 59
Tables 64
Figures 143
APPENDIX I NOTATION 163
APPENDIX II ESTIMATE OF THE PERCENTAGE OF STRUCTURAL CONCRETE THAT NEEDS REPLACEMENT IN A HEAVILY DAMAGED BUILDING. SURVEY OF PROFESSIONALS IN THE AREA OF EARTHQUAKE ENGINEERING. 164
APPENDIX III SOLICITATION OF ADVICE FROM EQUIPMENT PRODUCERS ON THE DESIGN OF CONCRETE RECYCLING PLANTS (LETTER) 165
APPENDIX IV REQUEST FOR CRITICAL REVIEW OF FINISHED DESIGN (LETTER TO EQUIPMENT PRODUCERS) 169

LIST OF TABLES

Table #	Title	Page
1	Compressive Strength of the Recycled Specimens and of Controls	64
2	Volume Changes of Concrete Cylinders Stored in Water	65
3	Consistency of the Recycled Specimens and Their Controls	66
4	Comparison of Properties of Uncontaminated Recycled Aggregate Concrete and Natural Aggregate Concrete of Similar Composition	67
5	Damage Probability Matrix for Buildings	68
6	Definition of Damage States for Buildings and Concrete Debris Generation	69
7	Definition of Damage States for Highways and Concrete Debris Generation	70
8	Concrete Debris from Buildings: San Fernando Earthquake of 1971	71
9	Rapid Estimate of Building Square Footage Damaged in the San Fernando Earthquake of 1971	72
10	Rapid Estimate of Damaged Space Versus Data-Based Estimate. Comparison of Results	75
11	Processable Quantities of Concrete Debris Each Year	76
12	Equipment for a Recycling Plant of 120 to 300 TPH Capacity	77
13	Equipment for a Recycling Plant of 300 to 450 TPH Capacity	78
14	Equipment for a Recycling Plant of 450 to 600 TPH Capacity	79
15	Equipment for a Recycling Plant of 600 to 750 TPH Capacity	80
16	Concrete Recycling Plants. Current Practice	81
17	Existing Methods of Concrete Cutting	88
18	Production Cost Estimate for the Recycling Plant	89
19	Initial Investment in the Sanitary Land Fill System	91
20	Manpower Requirements and Cost for Recycling Plant	92
21	Hourly Overhead Cost	93
22	Hourly Interest and Insurance	94
23	Hourly Production Cost	96
24	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 0.5 million tons.	97

List of Tables, Continued

Table #	Title	Page
25	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 1.0 million tons.	101
26	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 2.0 million tons.	105
27	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 3.0 million tons.	109
28	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 4.0 million tons.	113
29	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 5.0 million tons.	117
30	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 6.0 million tons.	121
31	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 7.0 million tons.	125
32	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 8.0 million tons.	129
33	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 9.0 million tons.	133
34	Economics - Net Present Value Analysis of Debris Recycling. Total Quantity of Concrete Debris Produced: 10.0 million tons.	137
35	Net Present Value and Internal Rate of Return for Recycling Systems	141
36	Composition and Costs of Natural Aggregate Concrete and Recycled Aggregate Concrete of Equivalent Performance	142

LIST OF FIGURES

Figure #	Title	Page
1	Relationship between Age and Compressive Strength Water to Cement Ratio is 0.55	143
2	Relationship between Water to Cement Ratio and 28-Day Compressive Strength	144
3	Modulus of Elasticity in Compression as a Function of Age. Water to Cement Ratio is 0.55	145
4	Methodology for Estimating Concrete Debris Generated from Buildings	146
5	Density of Building Space as a Function of Distance from Center of Urban Area	147
6	The San Fernando, California, Earthquake of February 9, 1971; Zones of Modified Mercalli Intensity (Note: Shaded area represents urban area.)	148
7	Concrete Debris Generation	149
8	Clearance of Concrete Debris Following a Natural Disaster	150
9	Material Balance of Plant for Recycled Concrete Aggregate	151
10	Schematic Design of a Recycling Plant with a 120-300 TPH Capacity	152
11	Schematic Design of a Recycling Plant with a 300-450 TPH Capacity	153
12	Schematic Design of a Recycling Plant with a 450-600 TPH Capacity	154
13	Schematic Design of a Recycling Plant with a 600-750 TPH Capacity	155
14	Perforated Plate Screen for Separating Re-bars or Other Long Objects from Granular Debris Material	156
15	Operation of Coarse Material Washer	157
16	Preliminary Cleaning Operations	158
17	Relationship between Required Initial Investment in a Concrete Recycling Plant and Plant Capacity	159
18	Guide for Estimating Hourly Cost of Interest and Insurance	160
19	Relationship between Production Cost and Plant Capacity in a Recycling Concrete Plant	161
20	Production Cost of the SLF System	162

CHAPTER 1

INTRODUCTION

Concrete debris is generated steadily as a result of the "normal" death of structures. Successful recycling of such debris and especially its use as aggregates for new concrete, is highly desirable because it can contribute to the solution of serious problems. Major natural disasters also lead to production of large amounts of concrete debris. Successful recycling of debris from a major natural disaster is even more desirable because it promises to solve particularly severe problems.

Several metropolitan areas are presently experiencing serious waste disposal (43) and aggregate availability (28,29,40) problems. Concrete is the most popular construction material and the most abundant one in demolition debris: it accounts for 67% by weight of all demolition debris (56). Disposal of such massive quantities of concrete waste poses a difficult problem due to the decreasing availability of dumping areas. At the same time urban expansion has led to closing of some aggregate plants and stricter environmental laws have led to closing of still others. For these reasons, aggregates are locally unavailable in several metropolitan areas. Consequently, the bulky and heavy aggregates have to be transported from increasingly longer distances at a greatly increased cost. These problems could be largely solved if concrete debris which is produced daily following the "normal" death of structures were to be recycled and used as aggregates for new concrete.

Serious as they may be, the debris disposal and aggregate availability problems described above cannot compete in severity with similar problems in the wake of a major disaster. In the latter case, immense quantities of concrete debris are produced: a large metropolitan area produces every year a few hundred thousand tons of concrete debris (15). By contrast, an earthquake of the intensity of the San Fernando earthquake of 1971 produces a few million tons! This ocean of concrete debris would have to be dumped. Later, during reconstruction following the disaster, there is a large demand for materials, with resulting shortages and price inflation (19). Concrete recycling as concrete aggregate following a natural disaster would go a long way towards solving these waste disposal and availability problems at the savings of millions of dollars and in an environmentally responsible way.

Recycling of concrete debris following a major disaster presents us with special problems: the quantities of debris produced exceed by far the quantities of debris normally produced. On the other hand, while an urban area produces a constant flow of concrete debris for the years to come, the debris quantity produced by the natural disaster is a one-time event. It follows that the optimal recycling technology and the resulting economies in the case of a natural disaster will be very different from what is normally encountered.

Previous work (for instance Ref. 4,15,56) in the area of concrete debris recycling is limited to debris produced during the normal death of structures and does not address the special problems - and outstanding benefits - of concrete recycling following a natural disaster.

This report is the end product of a study designed to assess the feasibility of recycling concrete debris as aggregate in areas that have suffered destruction. The specific objectives of the study were to determine:

1) The technological feasibility of concrete recycling as aggregate for new concrete.
2) The quantities of concrete debris produced following a natural disaster as a function of the intensity of the latter.
3) The optimal recycling technology as a function of the quantities of concrete debris to be processed.
4) The economic feasibility of concrete recycling following a natural disaster.

An assessment of the technological feasibility of concrete recycling is presented in Chapter 2 of this report. Previous work on the topic (4,16,18,27,39) has established that pieces of old concrete free from contaminants, such as gypsum, wood, plastics, etc., are a satisfactory substitute for natural aggregate in the production of new concrete. Additional studies and experience have shown (7,31,33,45) that of the contaminants in concrete debris, gypsum (calcium sulfate) is the least desirable because of the vulnerability of concrete to sulfate attack. Findings from previous studies of the effect of gypsum on the properties of concrete are not directly applicable to this work. Such studies have been motivated by additions of gypsum to cement, a step used by cement producers to control cement setting. Such additions involve very small quantities (1-3 percent by weight of cement) of finely pulverized gypsum. Accordingly, the above studies investigate the effect of relatively small quantities of pulverized gypsum on concrete properties.

On a building demolition site, gypsum is found mixed with concrete debris. As the latter is destined to become aggregate in the production of new concrete, the gupsum mixed with it will also become part of the new concrete. The amount of gypsum debris in the latter is a statistical quantity that can exceed by far the quantities of gypsum in previous studies. Moreover, the size of gypsum particles in recycled aggregate concrete is far coarser than the fine particles added by cement producers and studied previously.

It is useful to know the extent of the influence of gypsum debris on the new concrete under realistic conditions. If such influence is significant then a sorting system should be used to eliminate deleterious contaminants of concrete debris and the cost of the final product - recycled aggregate - is going to increase. In this work we have established realistic bounds of the effect of gypsum contaminant on the technological properties of new concrete so that an informed decision can be reached on whether such sorting is necessary. In order to enhance the present knowledge in the area we have also studied certain fundamental mechanical and physical properties of concrete produced with uncontaminated concrete debris as aggregate.

Characteristic quantities of concrete debris generated by an earthquake are assessed in Chapter 3. Such an assessment is necessary in light of the fact that the optimal recycling technology and the resulting economies are both a function of the scale of operation. We are not aware of any previously published work in either the general area of construction materials losses or the more specific area of concrete materials losses following an earthquake. Such paucity of published studies is somewhat surprising in view of the fact that the great bulk of material waste in an earthquake is in the form of demolition debris and most of the latter, 67% by weight, is concrete. The scope of this part of our study is limited to earthquake produced debris.

The design of four concrete recycling plants appears in Chapter 4. As many as fourteen concrete recycling plants are currently in operation (52). These are mostly portable plants, easily assembled at the site of concrete debris accumulation. They are typically associated with highway projects where the demolished pavement concrete is recycled into a base aggregate (9,42,52) and in one case (14) into aggregate for new concrete pavement. Concrete debris produced in the demolition of highways is free of contaminants and, for this reason, existing plants have no facilities for cleaning the processed debris. Typically, these plants are recycling a few thousand tons of debris in each highway project.

In previous work (15) one of the authors has designed a 180 TPH capacity plant that includes a sorting system for concrete decontamination.

In this work (Chapter 4) we have designed concrete recycling plants that can sort, crush and screen concrete debris at capacities of up to 750 TPH. These plants are based on standard, widely used equipment. In Chapter 4 we also assess the potential of more sophisticated technology that can be used in recycling operations of even larger scale.

The economics of concrete debris recycling following a natural disaster differ from what they would be following the "normal" death of structures. While in the latter case there is a constant flow of processable debris each year for the years to come, a natural disaster releases a huge flow of processable debris immediately.

Recycling of concrete debris following a natural disaster can best be handled through a combination of plants which operate for various short periods of time and are then relocated as the flow of debris decreases.

There are infinite such combinations of plants and operating periods. In this work (Chapter 5) we have studied in detail the economics of eleven such promising combinations in order to determine under which conditions investment in these recycling schemes is economically justified.

CHAPTER 2

TECHNOLOGICAL FEASIBILITY OF CONCRETE RECYCLING

2.1 INTRODUCTION

Concrete debris produced in the demolition of buildings is contaminated with a variety of materials, such as metals, bricks, gypsum, wood, plastics and glass. By contrast, the debris produced in the demolition of highways is free of contaminants. Sixty percent of concrete debris comes from the demolition of buildings; 15 to 20 precent of concrete debris comes from the demolition of highways (14).

Previous work in the area of technological feasibility of concrete recycling deals primarily with uncontaminated concrete debris. When the latter is used as aggregate in the production of new concrete, it has been established that:

1) best results can be obtained when concrete debris replaces coarse aggregate only (4);
2) The compressive strength of concrete produced with the recycled aggregate is somewhat lower than that of natural aggregate concrete (4,16,18,27,39). However, mix proportions of the recycled product can be manipulated to obtain equal strength with the conventional product (27).
3) The stiffness (16) and flexural strength (27) of concrete produced with recycled aggregate is somewhat lower than that of conventional concrete.
4) The freeze-thaw resistance (4,27), volume stability (4) and workability (4,16,27) characteristics of concrete based on recycled aggregate are similar to those of the conventional concrete.

Of the major contaminants in concrete debris, metals and bricks do not cause any problems if mixed into a new concrete. Both of these contaminants have high intrinsic strength, form a good bond with cement and, except in the case of bricks with a high sulfate content (31,45), do not react with cement.

Crushed glass has been experimentally used as aggregate in asphalt pavement (6,7,46), as well as in concrete. It is reported that crushed refuse glass has been substituted for about 30 percent of natural aggregate in Portland cement concrete (37). The results seem to indicate that problems involved in using waste glass in Portland cement products can be overcome and that the use of glass in concrete is feasible.

The presence of wood chips in concrete causes deleterious effects due to the presence of tannin. For this reason organic matter in general, and wood in particular, should be excluded from high quality concrete (33).

The possibility of sulfate attack on concrete due to the presence of gypsum (calcium sulfate) presents by far the most serious problem associated with the use of contaminated concrete debris as aggregate. Gypsum is found in building demolition in the form of plaster, wall-board and the like.

Previous work (5,10,23,25) has established that the presence of gypsum in concrete affects the rate of setting and volume stability of the latter. It has been shown that gypsum retards the early hydration of cements of high or moderately high tricalcium aluminate (C_3A) content and accelerates the hydration of cements of low C_3A content. Furthermore, it has been established that C_3A in Portland cement reacts speedily with gypsum under suitable physico-chemical conditions to form a complex calcium hydrosulfoaluminate compound. Formation of the latter, and its subsequent crystallization in the shape of thin needles or prisms, is accompanied by considerable increase in volume. Should hydrosulfoaluminate be formed during the early stages of hardening, when cement is still a viscous fluid, then it is a structurally useful compound, increasing the strength of the paste. The formation of crystalline sulfoaluminate in a hardened cement paste, however, is accompanied by a disintegration of the paste because of the growth of the voluminous crystals and the considerable strains arising as a result. (5)

Findings from previous studies of the exact effect of gypsum on the properties of concrete are not directly applicable to this work. Such studies were motivated by the small additions of pulverized gypsum used by the cement producers to control setting of cement. Accordingly, previous studies involve relatively small quantities of gypsum, the latter in the form of very fine particles.

On a building demolition site gypsum is found mixed with concrete debris. As the latter is destined to become part of the new concrete, the gypsum mixed with it will also become part of the new concrete. The amount of gypsum debris in the latter is a statistical quantity that can exceed by far the quantities of gypsum used in studies previously reported (5,10, 23,25). Moreover, the size of gypsum particles in recycled aggregate concrete is far coarser than the very fine particles added by the cement producers and studied previously.

Useful information on the effect of gypsum debris in concrete under realistic conditions can be gained from the German post World War II experience. At the time demolition debris was used as a construction material in Germany. The recycled debris consisted largely of brickwork, building blocks, isolated pieces of concrete and adherent lime or cement mortar and was used as concrete aggregates for the production of concrete roofs, floors and wall slabs (33). In spite of the fact that the resultant concrete has been found satisfactory, a warning appeared in a German publication of the time to the effect that where gypsum mortar or plaster board are present in the debris, care should be taken to ensure that the content of the soluble sulfate should not exceed 1% by weight of the cement and a qualitative test for sulfate was described (33). However, Germany at the time was in the early stages of its economic recovery and only limited attention had been paid to an indepth study of the influence of gypsum-contamination of concrete as aggregate. The meager data on the topic was not augmented by British publications of the time because, even though recycled demolition debris was used in this country as aggregate, gypsum-contaminated concrete was used only for filling, land reclamation and as a road-base material (33).

Most of the debris is contaminated and it is therefore useful to decide whether decontamination is necessary. To this end, it would be desirable to know the extent to which gypsum contamination of the debris affects the properties of the resultant concrete.

In this work we have established the bounds of influence of the gypsum contaminant of concrete debris on the strength of concrete produced with such contaminated debris as aggregate. In order to faithfully represent actual conditions we have used in our studies gypsum in the quantity and particle sizes that appear in the field. Furthermore, to provide a reference and to enhance our knowledge in the area we have studied the strength properties of concrete produced with uncontaminated concrete debris as aggregate.

Both types of recycled concrete debris (gypsum-contaminated and uncontaminated) have been additionally used as aggregates to study the workability, stiffness and volume stability characteristics of the resultant concrete.

The experimental variables studied in our work include the water to cement ratio, age of the specimens, type of portland cement used and degree of gypsum-contamination.

2.2 EXPERIMENTAL PROCEDURE

Previous work (4) on uncontaminated concrete debris as aggregate for new concrete suggested that best results are obtained when the recycled material is used as coarse aggregate only. Accordingly, in this work, waste materials were used solely as substitutes for coarse aggregates.

Concrete produced with natural coarse aggregate from the quarry was used as control. Additionally, several specimens of recycled aggregate concrete (RAC) were produced with uncontaminated recycled concrete aggregates and referred to in this work as "uncontaminated RAC." The latter, containing no gypsum contamination, provided an upper bound for the anticipated properties of gypsum-contaminated concrete.

The performance of concrete produced with gypsum contaminated concrete aggregate was compared to the performance of the control and of uncontaminated RAC. We have studied two degrees of gypsum contamination, recycled concrete (coarse) aggregate containing 5% by weight gypsum ("contaminated RAC") and coarse aggregate containing 100% gypsum ("gypsum-mortar mix"). We view the 5% gypsum contamination (by weight of coarse aggregate) as a conservative figure, whereas a 100% contamination level was used to get a lower bound for the anticipated properties.

In order to simulate the characteristics of actual concrete debris, gypsum was present in our mixes in pieces ranging from 1/16 to 3/4 in.

The effect of gypsum contamination depends on the amount of C_3A content present in the cement. Accordingly, we included in our study two types of portland cement: Type I with a high (11%) C_3A content, and Type II with a low (5%) C_3A content.

To study a possible latent expansion, we studied gypsum contaminated specimens aged up to 49 days.

To assess the effect of amount of water in the mix on the relative merits of contaminated and uncontaminated specimens, we studied four levels of the water to cement ratio.

2.2.1 Materials

The materials used in this study are listed below, together with a short description.

cement: In our experiments we produced specimens with portland cement Type I and additional specimens with portland cement Type II (ASTM C-150)

water: Potable tap water.

sand: Natural river sand, mostly fine-grained granite.

gravel: For control purposes, the coarse aggregate used was granite gravel, 50% crushed, from the quarry.

old concrete aggregate: Pieces of old concrete used as coarse aggregate in this work came from a 2-year old concrete slab produced in our laboratory and subsequently crushed with an electric demolition hammer. The slab was made of portland cement Type III (ASTM C-150), granite sand with a fineness modulus of 2.80 and granite gravel, 50% crushed, with a fineness modulus of 7.00. The ratio of cement to fine aggregate to coarse aggregate was 1:2:3 by weight and the water to cement ratio 0.50 by weight. Specimens produced from the same batches as the old concrete slab showed a 14-day strength of 3780 psi.

gypsum: Rehydrated, commercially available plaster of paris was our gypsum contaminant. It was crushed to a maximum size of 3/4 in.

2.2.2 Mixed Proportions

All control and RAC mixes were proportioned on a ratio of 1:2:3 by weight for cement, sand and coarse aggregate, respectively. The amount of water was varied to achieve water to cement ratios of 0.45, 0.55, 0.65 and 0.75 by weight, which were employed in connection to the compression and slump tests, while the water to cement ratio used in connection to the volume stability and stiffness tests was 0.55 by weight.

The same grading was used for coarse aggregate in all control and RAC mixes: maximum size 3/4 in, 60% retained on a 3/8 in sieve and 100% retained on a No. 4 sieve. In the contaminated RAC mixes, 5% by weight of each weight fraction of coarse aggregate was replaced by gypsum. The above amounts of gypsum in the specimens is equivalent ot a SO_3 content of 7% by weight of cement.

The gypsum mortar mixes could not be proportioned in the same ratio as the control and RAC mixes; to do so resulted in an unworkable mix without sufficient paste to coat all the gypsum-aggregate. These mixes were proportioned, instead, in a ratio of 1:2:2.25 by weight, for cement, sand and gypsum respectively. This is equivalent to a SO_3 content of 105% by weight of cement.

Fine aggregate used in all control, RAC and gypsum-mortar mixes was the same: natural sand with a fineness modulus of 2.80.

2.2.3 Geometry, Curing and Testing of Specimens

Compressive Strength Tests Concrete cylinders for the compression test had a diameter of 3 in and a height of 6 in. After casting, specimens were stored at 72°F and 100% R.H. until tested. At least 3 and usually more cylinders from each concrete mix were tested during the testing day according to ASTM C-39.

Modulus of Elasticity Tests The static modulus of elasticity in compression was determined for all concrete cylinders produced with a water to cement ratio of 0.55. This was accomplished by measuring the deformation of the specimen with a 3 in dial gage during the compression test.

Volume Stability Tests The same concrete cylinders with a water to cement ratio of 0.55 that were used for the 49 day compression test were also tested for expansion. The volumes of these cylinders were measured at 1, 14, 28 and 49 days of age by the following method: they were removed from the curing tank, dried until they achieved the saturated surface dry condition, and weighed, first in air, then in water. The volume, V was computed from the following formula (11):

$$V = \frac{(W_a - W_w)}{\gamma}$$

where W_a is the weight of the specimen in air, W_w is its weight in water, and γ is the specific weight of the water.

Slump Tests The workability (consistency) of all concrete mixes was measured with a 6-in-high cone. The latter was selected over the standard 12-in-high cone because of its moderate demands on materials quantities consistent with the relatively small cylinders produced. The smaller cone adequately served our purpose of comparing the relative workability of the RAC or gypsum-mortar mixes and of the controls.

2.3 RESULTS

Compressive Strength The compressive strength of all tested mixes is shown in Table 1. Values from this Table for a constant water to cement ratio of 0.55 and for both types of cement used have been plotted in Fig. 1 as a function of time. Additionally, strength data from Table 1, for a constant age of 28 days and for both types of cement used have been plotted in Fig. 2 as a function of the water to cement ratio.

In both Figures 1 and 2, curves B (zero gypsum contamination) and D (100% gypsum contamination) represent the upper and lower bounds, respectively for the compressive strength of gypsum contaminated specimens. Furthermore, in both of the figures above, the effect on strength of the replacement of natural aggregate with pieces of (uncontaminated) old concrete is reflected in the difference between curves B and A (control).

When natural aggregate was replaced with pieces of old concrete there was a decline in the strength of concrete from between 0 and 29%. There was a further decrease in strength as gypsum particles replaced the old concrete aggregates; this decrease was positively related to the amount of gypsum present: when gypsum replaced 5% of coarse aggregate the resultant decline in concrete strength was between 0 and 51%. When gypsum replaced 100% of coarse aggregate, the resultant decrease in strength was from 42 to 85% (Table 1, Figs. 1 and 2).

Use of portland cement Type II seemed to yield better results than those obtained with portland cement Type I with the contaminated RAC specimens. The difference was significant only at high water to cement ratios and with more advanced ages. On the other hand, gypsum-mortar specimens prepared with Type I and Type II cements had comparable strengths (Table 1, Figs. 1 and 2).

The relative merits of contaminated RAC, uncontaminated RAC and control do not seem to vary with time. In the gypsum-mortar specimens the rate of growth in strength is lower than that in the rest of the speciments. This is especially true for ages after 28 days where some of the gypsum-mortar specimens even experienced a decline in strength (Table 1, Fig. 1).

The water to cement ratio does not appear to affect significantly the relative merits of the contaminated RAC and its controls (Table 1 and Fig. 2). The gypsum-mortar specimens seemed to be less sensitive to the water to cement ratio than the rest of the specimens (Fig. 2).

Modulus of Elasticity Similarly to strength, the modulus of elasticity decreased when pieces of old concrete replaced natural coarse aggregate; this decline was between 2 and 10% (Fgi. 3). When gypsum replaced part of the old concrete aggregate there was a further decline in stiffness: the modulus of contaminated RAC was from 20 to 30% lower than that of the control (Fig. 3).

Volume Expansion Gypsum-mortar specimens stored continuously in water showed significantly larger volume expansions than did the rest of the specimens stored under similar conditions (Table 2). Gypsum-mortar specimens produced with portland cement Type II showed a smaller expansion than similar specimens produced with portland cement Type I (Table 2).

Workability The uncontaminated RAC and control were equally workable. Contaminated RAC was somewhat less workable, but the difference in workability (consistency) was not significant. Gypsum-mortar specimens were significantly less workable (Table 3).

2.4 DISCUSSION

When natural aggregate was replaced with uncontaminated pieces of old concrete, the resultant material had a strength of at least 71% that of the natural aggregate concrete. This finding is in agreement with findings in References 4, 16, 18, 27 and 39.

In natural aggregate concrete it is usually the aggregate-paste bond that is the weakest (strength determining) link, so that the fracture surface proceeds preferentially around the aggregate and through the aggregate paste interface so that the high strength of the aggregate is not utilized. It follows that the strength of concrete will not be significantly decreased if natural aggregate is replaced by a weaker material, provided that the aggregate-paste bond will continue to be the weakest link and that the strength of the bond will not be affected. This is the case when waste concrete aggregate is primarily gravel (16). When recycled aggregate particles are primarily mortar, however, they are weak enough to become the weakest link in the new concrete and it is due to the presence of this type of aggregate that the strength of concrete is reduced (16) relative to the natural aggregate concrete.

When gypsum replaced part or all of old concrete aggregate a further deterioration in strength was observed (Table 1). One reason for this is that gypsum aggregates are much weaker than the pieces of concrete they replace; weak enough to become the weakest link in concrete. An additional reason is that gypsum probably reacted with the C_3A in cement to produce an expansion that caused deterioration of the paste. This expansion was clearly seen in the case of gypsum-mortar specimens (Table 2). Furhtermore, an indication that there was a chemical reaction between the gypsum contaminant and C_3A in cement comes from the fact that the volume expansion of gypsum-mortar specimens based on Type II cement was smaller than the volume expansion of similar specimens produced with cement Type I (Table 2). Additionally, the strength of contaminated RAC based on Type II cement was greater than the strength of similar specimens produced with Type I cement (Table 1).

Our strength measurements in the contaminated RAC specimens did not show that gypsum affected the rate of strength growth (Table 1). Should gypsum in these mixes have acted either as a retarder or an accelerator, its effect should have ended before the age of 14 days, when our measurements started.

The recycled aggregate concrete or gypsum-mortar mixes had a lower modulus of elasticity than the control. This finding is expected since recycled concrete aggregate, as well as gypsum, have a lower modulus than natural aggregate and, in addition, it is well known that the modulus of concrete depends significantly on the modulus of its aggregates.

Replacement of natural aggregates by old concrete aggregate did not affect workability (Table 3). This was due to the good particle shape of recycled aggregates together with the fact that the latter were used in the saturated surface dry condition.

2.5 CONCLUSIONS

From the technological point of view, uncontaminated concrete debris is a satisfactory aggregate for the production of new concrete. RAC produced with uncontaminated concrete debris has a somewhat lower strength than natural aggregate concrete of similar composition. On the other hand, the mix design can always be manipulated to yield a product of similar strength. For instance, it can be seen from Fig. 2 that when portland cement Type I is used, natural aggregate concrete produced with a water to cement ratio of 0.75 has the same strength as does uncontaminated RAC produced with a water to cement ratio of 0.65

Findings from this and previous investigations summarized in Table 4 also confirm the technological adequacy of uncontaminated recycled concrete as aggregate for new concrete.

When gypsum contaminated concrete debris is recycled as aggregate for new concrete the strength and stiffness of the latter suffers a reduction the magnitude of which is positively related to the amount of gypsum in the mix. For instance, if gypsum in the new concrete mix comprises 5% by weight of the coarse aggregate, the strength of the product can be as high as 51% of the strength of natural aggregate concrete. In the extreme case where gypsum comprises 100% of coarse aggregate, the strength drops to 15% of the value of the control. In this case the strength of the mix is only about 700 psi. We conclude that concrete aggregate which has been contaminated with gyspum can be used in the production of low strength concrete only. In the usual case where a concrete strength of 3,000 to 4,000 psi is required, only uncontaminated concrete aggregate can be used. Accordingly in the design of recycling plants, which is presented below in Chapter 4, we have included sorting equipment that eliminates concrete debris contaminants.

CHAPTER 3

ASSESSMENT OF THE QUANTITIES OF CONCRETE DEBRIS PRODUCED IN AN EARTHQUAKE

To assess the economic feasibility of concrete recycling following an earthquake it is necessary to estimate the quantities of generated concrete debris: a prerequisite for the economic justification of concrete debris recycling is the presence of sufficiently large quantites of concrete debris so that a recycling plant of optimal size can be operated at high utilization factors.

In this part of our work we have developed a method for estimating the quantities of concrete debris produced from building and highway damage in an earthquake as a function of the intensity of the earthquake and of the specific construction characteristics of the earthquake stricken area. Our method can be used by persons in decision-making positions in disaster areas to arrive rapidly at an estimate of the quantities of such debris. By use of such estimates an informed decision can be reached on whether debris should be dumped or should be saved in a nearby location for economically justifiable recycling.

In the last part of this chapter we have applied our method to assess the quantities of concrete debris generated by the 1971 earthquake of San Fernando.

3.1 METHOD FOR ESTIMATING THE QUANTITIES OF CONCRETE DEBRIS: AN OVERVIEW

To arrive at an estimate of the amount of concrete debris generated from building damage in an earthquake, we have used a technique known as the Damage Probability Matrix (DPM)(Table 5). This matrix relates ground motion, defined in terms of earthquake intensities, to building damage, which is defined in terms of damage states defined verbally and in terms of costs in Table 6, Col. 2 and 3. The matrix can be used to estimate the percent of total square footage in the earthquake area in each damage state. Although the DPM is applicable to non-wooden construction only, its usefulness in our study is not decreased, since in wooden construction concrete is used in the foundations only and the latter are considered not recyclable.

We are only interested in structural damage, since concrete is a structural material. Such damage will only be generated at damage states which are considered "heavy" and "total" ("none," "light" and "moderate" damage states produce no structural damage [Table 6]). Furthermore, earthquakes of Modified Mercalli Intensities (MMI) less than VII normally produce negligible structural damage. Accordingly we have limited ourselves to a condensed version of the DPM shown in heavy brackets in Table 5: it includes only "heavy" and "total" damage states and earthquake intensities of MMI VII or higher.

For the purpose of this study it was convenient to redefine (Section 3.2) the "heavy" and "total" damage states in terms of the amount of concrete per square foot of building space that needs replacement in each of the above states.

To obtain an estimate of the total square footage in each damage state, and thereby estimate the total amount of debris in the earthquake area, we based ourselves on the building inventory in the area. (Through use of the DPM the latter is allocated to the various damage states.) Data on the building inventory for most areas in the U.S. is not readily available. For this reason, and because such data is needed soon after the disaster for optimal decision-making with regard to concrete debris, we describe, in Section 3.3 below, a method for obtaining a quick estimate of building inventory in the affected area.

The total amount of concrete debris generated in each of the damage states constitutes the total tonnage of concrete debris (Section 3.4).

An outline of our method for building damage estimation appears in Fig. 4.

We have devised a similar method for estimating the quantities of concrete debris generated from highway damage in the earthquake area (Section 3.5).

3.2 AMOUNT OF CONCRETE PER SQUARE FOOT OF BUILDING SPACE THAT NEEDS REPLACEMENT IN A HEAVILY OR TOTALLY DAMAGED BUILDING

All concrete debris is produced in the structural damage producing states designated "total" and "heavy" (Table 6). When the damage is "total," 100% of concrete in the structure joins the debris category (Table 6, Col. 4). The question then is: "Under heavy damage, what percentage of structural concrete needs replacement?".

To answer this question we contacted seven experienced professionals and scholars in the area of earthquake engineering and asked them to provide us with an estimate of the percentage of concrete that would have to be replaced in a heavily damaged building (see Appendix II). Their estimates ranged from 5 to 25%, with an average of 11.2%. Accordingly, in this study we have assumed that 11% of structural concrete has to be replaced in a heavily damaged building (Table 6, Col. 4).

To translate the above percentages into tons of concrete per square foot, we had to know the concrete content per square foot of building construction. This was estimated in the following manner:

1) For each one of the last 10 years, the amount of concrete consumed in the United States for the construction of building space was divided by the amount of building square footage produced in that year. From the numerators we subtracted in each case the amount of concrete used for basements and foundations, as this amount is not recycled, and from the denominators we subtracted the square footage of wood-based construction. The latter is far more resistant to earthquakes (34) and contains no recyclable concrete. The figures we derived for the last 10 years

ranged from 0.04 to 0.10 tons of concrete per square foot of building space with an average value of 0.084 tons per square foot.

2) The amount of concrete in four typical non-wood frame buildings was calculated and found to range from 0.036 to 0.08 tons per square foot, with an average value of 0.057 tons per square foot.

Based on the results of the above two estimating methods we assume below that, on the average, 0.06 tons of concrete are used per square foot of building construction.

We combine our findings to derive that 11% of structural concrete of 0.06 tons per square foot, that is, 0.0066 tons of concrete per square foot, needs replacement in a heavily damaged building. Furthermore, 100% of structural concrete, or 0.06 tons per square foot needs replacement in a totally damaged building. The above is reported in Table 6, Col. 5 and constitutes a definition of damage states in terms of concrete debris generation.

3.3 AMOUNT OF SQUARE FOOTAGE WHICH IS HEAVILY OR TOTALLY DAMAGED

To arrive at an estimate of total square footage in each of the damaged states "heavy" and "total" requires knowledge of the inventory of building space in each of the areas which has suffered MMI VII or higher (Table 5). Once the above inventory is known, one can use the DPM in Table 5 to allocate it into the "heavy" and "total" damage states; and to derive the total amount of damaged square footage, one has to sum up the damaged square footage in each region that has suffered an MMI VII or higher (see Fig. 4).

A difficulty in the application of this method is presented by the fact that an inventory of building space is not readily available for most areas in the country. Given the appropriate resources, such information can be obtained rather awkwardly from several sources. For instance, one can use very detailed maps (scale 1/600 to 1/200)(47) that exist for all but rural areas in the country. These maps contain a plan view of buildings (from which one can derive the square footage per story), information on the number of stories (which yields the total square footage per building), the end-use of the building (whether an apartment or office building, etc.), and the basic structural material (which allows exclusion of wood-based square footage). To cover an area as small as a county one might have to accumulate information contained in about 40 volumes of maps: a process that may require a few months at a cost of a few tens of thousands of dollars.

Alternatively, one can use one of the existing data sources on on-going construction projects (for example, Ref. 13) to derive the inventory of building space. The above data exists for the last decade in detailed and comprehensive form and includes square footage of buildings and basic structural material. One can therefore sum up the non-wood based square footage built during the last 10 years in the area and then make the assumption that the above sum represents a given fraction of the total inventory in order to arrive at an estimate of the total inventory. To apply this method, the required information from the data files has to be collected and summed up at an expense of time and money.

Following an earthquake, quick decisions have to be made on the fate of concrete debris: should it be disposed of in a dump or should it be recycled as concrete aggregate? The answer to the above depends on the quantity of generated concrete debris, which has to be rapidly assessed. The latter depends, in turn, on a rapid assessment of the building inventory.

To arrive at the desired rapid estimate of the inventory of building space in an area that has suffered an earthquake of given intensity, we suggest the following:

a) By personal inspection (flying over or driving through) of the earthquake stricken area (or even better, from an isoseismal map, if one is available) assess the square mileage of urban land that has suffered a given earthquake intensity (in this case, an intensity of MMI VII or higher).

b) Similarly, assess the location of a "spot" (say, about 0.10 square miles), in the above areas which is representative in terms of building density.

In the case study that follows, we have made the assumption that building density decreases linearly with distance from the center of the urban area (this assumption is supported by published data; see, for instance, Ref. 2). For areas where the above assumption holds, if BC (Fig. 5) is a diameter of the area which has suffered a given earthquake intensity and D is the center of this area, then the density at D is representative of the average density in the area. Of course, if A, the center of the urban area, is close to center D of the earthquake stricken area, then another "spot" in between D and C or D and B has to be chosen as representative.

c) Once a representative "spot" D has been decided upon, building density in an area limited geographically to the very small region that D occupies is assessed through use of very few maps (17) or other available data on building density. Because of the very limited area of coverage, information on building density can be obtained speedily in this manner at a cost of few tens of dollars.

d) Multiply building density, in square feet per square mile of land at the representative "spot" D (derived in step "c" above) by the total square mileage derived in "a" above, to arrive at the total inventory of space in the area suffering a given earthquake intensity.

3.4 TOTAL TONNAGE OF CONCRETE DEBRIS GENERATED

Through use of the DPM (Table 5), the total inventory of building space in the area is allocated to the various damage states. The square footage in each of damage states "heavy" and "total" is then multiplied by the amount of concrete debris generated per square foot in the above states (after Table 6). The total tonnage of concrete debris produced is the sum of debris produced in each of the damage states "heavy" and "total" (see Fig. 4).

3.5 HIGHWAY DAMAGE ESTIMATION

A DPM for highways, similar to the one in Table 5 which was developed for buildings, apparently is not available at this time. Therefore, one has to rely on an actual survey of damaged mileage. Fortunately, such a survey can easily be done: most highway damage is conspicuous, and an aerial inspection may readily give a good idea of the extent of damage suffered. For instance, by flying over the destroyed region one can determine that approximately "x" highway miles suffered "heavy" and "y" miles suffered "moderate" or "minor" damage. What is needed, then is a definition of damage states for highways, both verbally and in terms of percentage of concrete that needs replacement.

We have critically reviewed the literature on highway damage by earthquakes and, on this basis, have derived the definition of highway damage states given in Table 7, Columns 1 to 3. In the same Table we derive the amount of concrete debris generated from highway damage (Col. 4) by multiplying the percentage of concrete that needs replacement in the various damage states (Col. 3) with a concrete content of 6600 tons per highway mile (22).

3.6 CASE STUDY: THE SAN FERNANDO EARTHQUAKE OF 1971

We have applied the method described above to estimate the quantities of concrete debris generated in the San Fernando earthquake of 1971. We selected the above case because of the excellent damage statistics that exist (see, for example, Refs. 3,49,50, and 53).

3.6.1 Concrete Debris Generated from Building Damage

During the San Fernando earthquake of 1971, 65 apartment buildings and 574 commercial-industrial buildings were totally damaged, while 265 apartment buildings and 1125 commercial-industrial buildings were heavily damaged (3)(Table 8, Col. 1 and 2).

Ninety-nine percent of the surviving buildings had 1 to 3 stories (34) and most of them used wood as the major structural material (wood-based construction has superior earthquake resistance (34,48). We have made the assumption that the majority (80%) of non-wood based buildings that suffered major damages during the above earthquake had 3 stories or more; furhtermore, of the above buildings (80% of the total), apartment buildings had an average floor space of 110,000 square feet, and commercial-industrial buildings had an average floor space of 130,000 square feet (53). The additional 20% of damaged buildings had an average floor space of 11,000 and 13,000 square feet for apartments and commercial-industrial buildings, respectively. Using the above, the average square footage of damaged apartment buildings in the area was calculated to be 0.8 x 110,000 + 0.2 x 11,000 = 90,200 square feet, while that for commercial-industrial buildings was 0.8 x 130,000 + 0.2 x 13,000 = 106,600 square feet (Table 8, Col. 3).

The total amount of concrete debris generated from buildings is estimated in Table 8 as follows: the number of damaged buildings multiplied by the average square footage per building gives the number of damaged square feet. The latter is multiplied by the tons of concrete debris generated per square foot of damaged space to give the total amount of concrete debris generated from buildings.

As can be seen from Table 8, a total of about 5 million tons of concrete debris was generated from buildings in the San Fernando earthquake. The above estimate is based on actual data on the number of severely damaged buildings and their square footage (3,53). This is the type of data that typically become available between several months and a few years after an earthquake.

For a rapid estimate of severely damaged space in the San Fernando earthquake of 1971 we have used the method described in Section 3.3 of this paper and have then compared our results with the field data appearing in Table 8, Col. 4.

The rapid estimate involved the following steps:

a) From the isoseismal map for the San Fernando earthquake of 1971 appearing in Fig. 6, we estimated that 437 square miles of urban area suffered an earthquake intensity of VII, 69 square miles suffered an earthquake intensity of VIII and finally, 13 square miles suffered an earthquake intensity of IX (Table 9, Col. 2).

b) The area centers in the above areas were taken as representative "spots" in terms of building density. The latter are at distances of 5, 17 and 22 miles from the center of Los Angeles for areas experiencing intensities of VII, VIII and IX, respectively (Table 9, Col. 3).

Residential and non-residential space has been studied separately in order to test our method in greater detail.

c) The representative densities derived above have been multiplied by the total square mileage suffering a given intensity to derive an estimate of the total affected square footage (Table 9, Col. 5 and 11).

d) Of the total affected square footage, one-third had been designed according to Uniform Building Code (UBC) zoning 0 requirements and the remaining two-thirds according to UBC zoning 3 requirements (53)(Table 9, Col. 6,7,12 and 13). In each case, the percentages reported in the DPM in Table 5 have been used to allocate the square footage to the "heavy" and "total" damage categories (Table 9, Col. 8,9,14 and 15). It was found that 6.45 million square feet of residential space was totally damaged and an additional 14.61 million square feet of residential space was heavily damaged. Furthermore, 73.4 million square feet of non-residential space was totally damaged and an additional 165.18 million square feet of non-residential space was heavily damaged (Table 9).

The above results of our estimation procedure are compared in Table 10 with results based on field data. From the above Table, it can be seen that our rapid estimates of damages space are on the average within 18% of the more accurate estimates based on field data and in no case deviate more than 39% of the more accurate results.

3.6.2 Concrete Debris Generated from Highway Damage

A total of 66 bridges with a total length of 6 miles suffered some damage in the San Fernando Earthquake of 1971 (3). Of these, about 25%, or 1.5 miles, sustained heavy damage; 50%, or 3 miles, sustained moderate damage and the rest was only damaged in a minor way. (Derived from data in Ref. 3.) Based on the above and using the numbers in Table 7, Col. 4, the total tonnage of concrete debris generated from bridge damage was derived: 1.5 miles x 6600 tons/mile + 3 miles x 660 tons/mile, or 11,880 tons of concrete debris.

In addition, a total of 35 highway miles was damaged. Of these, 15% or 5.25 miles, was heavily damaged and 40%, or 14 miles, was moderately damaged. (Derived from data in Ref. 3.) Therefore, the total amount of concrete debris from highway damage was (see Table 7, Col. 4): 5.25 miles x 6600 tons/mile + 14 miles x 660 tons/mile, or 43,890 tons of concrete debris.

For both bridges and highways, the total amount of concrete debris generated was 11,880 + 43,890, or 0.0557×10^6 tons.

3.6.3 Total Amount of Concrete Debris Generated in the San Fernando Earthquake of 1971

The sum of concrete debris generated from building damage (estimate based on field data) and highway damage in the San Fernando earthquake of 1971 is $5.0122 \times 10^6 + 0.0557 \times 10^6$ or 5.07×10^6 tons.

3.7 SUMMARY AND CONCLUSIONS

Following an earthquake, decisions have to be reached on whether the quantities of concrete debris generated are large enough to justify recycling. To assess the tonnage of generated debris, one has to know the quantity of debris generated per square foot of damaged space and the total amount of damaged square footage.

In this study, we have estimated the quantity of concrete debris generated per square foot of damaged space for each damage category.

Once the inventory of building square footage is known for an area which has suffered an earthquake of given intensity, one can use the estimation technique known as Damage Probability Matrix to allocate the existing square footage into the various damage states and thus arrive at an estimate of the tonnage of concrete debris produced during the catastrophic event.

For cases where the building inventory in the earthquake stricken area is not known, we have suggested a rapid method for estimating this inventory and have subsequently used our method in a case study for which adequate field data exists. Results from the suggested rapid estimate were of the same order of magnitude as those estimated on the basis of actual data (Table 10).

We have applied our method for assessing the quantities of concrete debris produced by an earthquake in the specific case of the San Fernando earthquake of 1971. Our results show that 5×10^6 tons of concrete debris were generated in the above earthquake. It is remarkable that this amount is 16 times the amount of concrete debris generated annually in an area such as the Boston metropolitan area (15) and about 17% of the amount of concrete debris generated annually in the entire U.S. (56).

A summary of the quantites of concrete debris generated from "normal" and "violent" death of structures appears in Fig. 7. A few <u>thousand</u> tons of concrete debris are produced in a highway project involving demolition of the old pavement (41). A few <u>hundred thousand</u> tons are produced every year in a large metropolitan area (15). A few <u>million</u> tons of concrete debris are produced in a major natural disaster.

In order to cover most of the range of quantities of concrete debris produced in a natural disaster we have studied the recycling economics of concrete debris quantities ranging from 0.5 to 10 million tons.

CHAPTER 4

RECYCLING TECHNOLOGY

4.1 INTRODUCTION

Based on published data on the post-disaster era (19) we have assumed a 6-year reconstruction period matched with a 6-year debris clearance period. Furthermore, we have assumed that debris clearance following a natural disaster decreases linearly with time and that construction of a recycling plant in the disaster area is completed by the sixth month following the disaster. During the latter period any debris which is removed will not be recycled but rather will be dumped. The above assumptions are depicted graphically in Fig. 8.

To avoid significant debris accumulation at the recycling plant we have additionally assumed that the quantities of debris removed each year from the site will be recycled and sold as aggregate during the same year. This implies that aggregate demand for reconstruction follows the same pattern as debris removal.

Based on the above assumptions and for a total amount of debris generation ranging from 0.5 to 10 million tons we have derived the annual processable quantities of concrete debris in Table 11.

By use of the information in this Table we have designed 4 recycling plants with capacities ranging from 120 to 750 TPH. This implies that, if operated at full capacity, the largest of the designed plants will process about 1.5 x 10^6 tons of debris per year. Larger plant capacities are not justified in light of the fact that the disaster generated (debris) input to these plants decreases linearly with time to zero at the seventh year after the disaster.

Most of concrete debris originates during the demolition of buildings (14) and is thus contaminated with gypsum, wood, plastics, glass and metals. For this reason the recycling plants designed in this work include sorting processes.

On the average, 67% by weight of demolition debris is concrete (56). Steel members and copper pipes have an attractive resale value and are therefore reclaimed at the demolition site. This increases the concentration of concrete in the demolition debris arriving at the plant. Furthermore, as will be discussed below, we have adopted a charging system for the debris dumped in the plant which will encourage further the increased concentration of incoming concrete. For these reasons we have assumed that, of the demolition debris arriving at the recycling plant, as much as 75% by weight is concrete (Fig. 9).

Our estimates have shown that it is economically advantageous to have a sanitary land fill (SLF) adjacent to the concrete recycling plant in order to avoid the high transportation cost associated with disposal of non-concrete debris in a distant dump. Consequently, in the plant designs that follow we have assumed a SLF of this type. The capacity of the latter to absorb non-concrete debris will determine the life of the recycling plant at the site.

There is a choice between a portable and a stationary recycling plant The disadvantage of a portable plant is that standard portable equipment is of small to medium capacity. For this reason, when standard equipment is used, a portable system cannot take advantage of the more efficient large capacity equipment used in large scale operations. On the other hand, a portable system offers flexibility: the recycling plant can be relocated when processable debris in the area has been decreased to the point where plant operations are not economically justified or the plant can be relocated in the same general area next to a new SLF when the old SLF is filled. Because of the overriding need for flexibility, all plants designed in this work are portable ones.

4.2 DESIGN OF CONCRETE RECYCLING PLANTS

To design the recycling plants described below, we have critically reviewed the literature on presently existing recycling plants (9,15,38, 41,42,43,52) (The latter are of relatively small capacity and without any sorting facilities.) Secondly, we contacted several manufacturers of equipment used in recycling plants and invited their help in the design of the four plants describe in this report (see Appendix III, Letter to the Manufacturers). Three of the manufacturers whom we contacted responded with useful suggestions. After completing a preliminary design we again invited the comments of the above manufacturers and incorporated some of their suggestions in the design (see Appendix IV, Second Letter to the Manufacturers).

Our final designs appear schematically in Figures 10 to 13, while a list of equipment and associated costs appears in Tables 12 to 15. The designed plants have capacities of 120 to 300 TPH (Fig. 10, Table 12); 300 to 450 TPH (Fig. 11, Table 13), 450 to 600 TPH (Fig. 12, Table 14) and 600 to 750 TPH (Fig. 13, Table 15). All equipment selection is based on existing models.

The various steps in the recycling of concrete debris together with a materials balance for each of the four plants appear in Fig. 9. The first process involves preliminary cleaning and size reduction. This is followed by primary crushing, magnetic and manual separation of ferrous debris, sorting of lightweight impurities and, finally, secondary crushing.

Preliminary Cleaning and Size Reduction Debris brought to the recycling system mostly consists of concrete pieces with embedded steel re-bars or wire meshes. Additionally, there are considerable quantities of wood and brick, together with small quantities of gypsum, plastics and glass (Fig. 9). At the preliminary cleaning stage, one or more bulldozers are used to pick up large pieces of non-concrete debris.

Concrete pieces too large to be fed into the recycling system have to be reduced in size. For this purpose, the designed plants use one or more hydraulic hammers mounted on backhoes (with buckets removed). Steel rods longer than two feet are unacceptable with most of existing systems (52) and are therefore cut into shorter lengths by re-bar cutters.

Primary Crushing After preliminary cleaning and size reduction operations, the debris is fed into a hopper-feeder and through the latter into a screen which separates it into two categories: larger than 4" debris which has to go through primary crushing, and smaller than 4" debris which bypasses primary crushing.

Feeding equipment used in all 4 plant designs includes front-end loaders. Additionally, in the two larger plants, we have included a dragline crane with bucket to assist in the feeding operation. Following the above equipment comes a vibrating feeder and hopper which regulates the flow of debris into a screen. The latter in the three larger plants designed in this work is a perforated plate, as shown in Fig. 14, which sorts out steel rods unattached to concrete before they get fed into the primary crusher.

We have followed common practice in concrete recycling (Table 16) in selecting a jaw type primary crusher. Concrete debris entering the jaw crusher still carries attached steel bars. For this reason we have selected heavy duty jaw crushers that also contain some type of tramp-iron-release device (8).

In the jaw crusher steel rods are physically separated from concrete and are discharged lengthwise through the discharge opening of the crusher to the under-crusher belt conveyor. If the headroom between the discharge opening and the under-crusher belt conveyor is not large enough, long steel rods may just stay half-way through the discharge opening and block the opening. A previous operation at Taylor, Michigan (22) elevated the jaw crusher 6-8 ft above the under-crusher belt conveyor and also installed a turning type chute below the discharge opening so that discharged steel rods hit the conveyor belt at a less damaging angle. With standard portable systems one cannot obtain a 6-8 ft headroom below the discharge opening. For this reason we have used in the plants designed in this work an under-crusher belt conveyor that has a spring adjustment and can therefore be moved downward when a long steel rod forces through and blocks the discharge opening.

Magnetic and Manual Separation of Ferrous Debris After the steel rods have been effectively separated from the concrete pieces in the jaw crusher, they are sorted out manually, when long, or else by an overhead magnetic separator and magnetic head-pulley installed at the end of a long (50 ft) and wide (42 in) belt conveyor which serves as a "picking table." This is the same belt conveyor with the spring adjustments immediately following the jaw crusher.

In order to avoid complete shut-down of the system in case of malfunctions caused by the steel rods, a surge pile, in the design of the three larger plants, has been used to serve as a relay so that downstream operations (e.g., secondary crushing, washing and screening) can operate independently of the upstream operations (e.g., feeding, primary crushing and magnetic sorting). The surge pile system consists of a trench in the ground with belt conveyor and feeder installed.

Sorting of Lightweight Impurities The latter mostly include gypsum, in the forms found in construction, wood chips and plastics.

To sort out the above materials, one can adopt one of the many processes used by the aggregate processing industry. In this work we have followed the advice of people in the industry (35) in selecting a screw type washer dewaterer (Fig. 15) which simultaneously separates and sorts lightweight impurities and dewaters the washed aggregate so that the latter can be sent directly to a secondary crusher.

Secondary Crushing Following the screw washers-dewaterers is a screen which directs the larger than 1.5 in aggregate to further size reduction in a cone crusher. The latter is of the short-head type operating in closed circuit (Figs. 10 to 13). Selection of a cone type secondary crusher follows the concensus of experience (Table 16) and is based on the fact that this type of crusher produces a relatively coarse aggregate consistent with the requirement that recycled concrete be used as coarse aggregate only.

(The alternative would have been a crusher based on grinding or impact action, e.g. an impactor, which produces a much finer product.)

Additional Operations in the Recycling Plant These include stock-piling operations handled through the use of radial stackers and water supply and power generation operations.

4.3 POTENTIAL OF NEW TECHNOLOGIES FOR THE RECYCLING PLANTS

The design of the concrete recycling plants presented in section 4.2 above is based on standardized, widely used equipment. For very large plant capacities one may consider use of more sophisticated technology. For instance Table 17 lists certain rather sophisticated methods for preliminary size reduction of the concrete debris and considers their limitations. Most of these methods are good for special situations only. For instance, thermic lancing, an insatiable user of energy, is advisable as a means of concrete cutting only in cases where noise restrictions prevent the use of more rapid but noisier methods.

It has been suggested (55) that a water jet cutting system is potentially attractive for preliminary size reduction of concrete debris. Presently, there is intensive research but as yet no commercial applications in this area. Water jets have been used commercially, however in other applications, such as mining operations (24), dismantling of railway boxcars (51), cleaning ships' hulls (21) and quality cutting such as cutting shoe parts from synthetic materials (26).

In a water jet cutting system, a thin stream of water passes through a braided hose to a hand-held lance that is fitted with water flow controls and nozzels selected for their cutting efficiency.

To cut concrete, water pressures of about 10,000 psi are used, the exact pressure depending on the desired rate of cutting. At higher pressures one can cut higher strength materials, for instance, at a water pressure of 150,000 psi one can cut steel. A British manufacturer of pump equipment has carried out tests with water jets plus an added abrasive. In these tests a 3-inch thick reinforced concrete pipe was cut using a 150 HP pump and a water pressure of about 10,00 psi (24)

Among the advantages of water jets is their maneuverability, which is higher than that of equipment in Table 17. Concrete pieces may simply be shot by a high pressure water stream from a lance handled by a worker. This avoids a lot of positioning of equipment which is usually necessary for other types of size-reduction equipment (e.g., crane or drop-ball). Alternatively, the water jet can be installed with mechanical control and acts as a traversed cutter.

Among the disadvantages of water jets are that the pumping equipment presently available is noisy; the water-cleanliness requirements are high; and the nozzles and controls are not sufficiently robust for use by unskilled personnel.

The economic attractiveness of water jet systems for concrete cutting cannot be assessed at this point because no such system has yet been developed to a commercial level.

A rather sophisticated sorting system for preliminary cleaning of demolition debris has been developed in Ref. 55 and is schematically shown in Fig. 16. In this scheme the incoming debris is cut to short lengths by a traversing cavitating water jet assisted by an overhead squeeze roller. Following this, pieces of ferrous metals are sorted out by a drum magnet, fine materials are separated through a vibrating screen and finally, lightweight material is sorted out by a suction fan. The remaining debris has to go through additional steps of sorting and crushing.

4.4 THE SANITARY LAND FILL ADJACENT TO THE PLANT

The size of the SLF (acreage and depth) is determined by the total estimated volume of non-concrete debris that will be disposed of there during the period of plant operations in the location.

A lining of 2 inches of asphalt and 6 additional inches of sand will cover the surface of SLF to prevent leaching problems.

The equipment needed at the SLF includes compactors (bulldozers) and scrapers. The latter will do the job of scraping soil out of the ground and spreading it later on the compacted debris.

CHAPTER 5

ECONOMIC FEASIBILITY OF CONCRETE RECYCLING

We have estimated the required investment in each of the recycling plants and SLF that we have designed. Additionally, for each of the above plants we have estimated the production cost per ton of recycled debris.

There are infinite combinations of plants and operating periods for recycling concrete debris produced in a natural disaster. For instance, a possible recycling scheme can involve 2 recycling plants that will be reduced to one and finally to none as the disaster produced inflow of debris diminishes (Fig. 8).

In this work we have studied in detail the economics of eleven such promising combinations. In order to determine the conditions under which investment in the studied recycling schemes is attractive we have made a net present value analysis and an internal rate of return analysis of investment in these schemes.

In the first part of the economic analysis we made the assumption that 100% of the recycled product will be sold at a set price. In the last part of the analysis we determine the conditions under which the above assumption holds by comparing the economics of recycled aggregate concrete to the economics of natural aggregate concrete.

5.1 INITIAL INVESTMENT IN THE RECYCLING PLANTS AND SLF's

Recycling Plant The total required initial investment in a recycling plant is the sum of the purchasing and set-up costs of equipment (Table 18, Col. 4). The former is derived from Tables 12 to 15 and is reported in Table 18, Col. 2. The latter - for equipment requiring set-up - is assumed to be 15% of the purchasing cost of equipment and includes engineering and erection expenses (Table 18, Col. 3).

The relationship between the required initial investment in the recycling plant and plant capacity is shown graphically in Fig. 17. It can be seen that in the case of initial investment there are no economies of scale.

SLF The required total initial investment in a SLF is the sum of land acquisition, excavation, lining, engineerng and facilities costs (Table 19, Col. 8).

We have assumed that the SLF is located at a distance of 12 to 15 miles from the center of the city where land sells for $10,000 an acre (22). The required acreage depends on the volume of non-concrete debris that will be disposed of in the SLF. The weight of the above non-concrete debris will be 33% of the weight of processed concrete debris (75% by weight of the incoming debris is concrete and 25% is non-concrete [Fig. 9]). An estimate of the total tonnage of non-concrete debris disposed of in the SLF throughout the life of the recycling system appears in Table 19, Col. 2. To convert this tonnage into volume, we assumed a fill density of 0.02 ton/cu ft (2). Once the volume of dumped debris was determined we estimated the required acreage by assuming that the SLF is a rectangle with a square floor equaling the required acreage and a constant depth of 100 ft (Table 19, Col. 3). The total land acquisition cost equals the required acreage times the cost of land per acre (Table 19, Col. 4).

We have assumed that the acquired land is a valley (for example, an old quarry) and that only 20 out of the 100 feet of required depth will be produced by excavation. The total excavation cost for the various recycling schemes can be found in Table 19, Col. 5. To derive this number we have assumed an excavation cost of $0.57/cu yd (22). The excavated volume equals the volume of a 20-ft deep rectangle having a basis equal to the acreage in Col. 3 of Table 19.

To prevent leaching problems the total inside surface area of the landfill rectangle will be covered with 2 inches of asphalt and 6 inches of sand. At a cost of $6.46/sq yd (22) the total lining cost appears in Table 19, Col. 6.

Additionally there are engineering costs (e.g., initial study and surveying) and costs for the various facilities (roads, fences, etc.). We have assumed that each of the above costs is $5,000 for all SLF studied in this work.

The equipment needed at the SLF includes compactors (bulldozers) and scrapers. The former have already been included in the cost of the recycling plant (see Tables 12 to 15). We have assumed that the latter will be rented and, therefore, their cost appears as part of the production cost in the next section.

5.2 PRODUCTION COST ESTIMATE FOR THE RECYCLING PLANTS AT THE SLF SITES

The production cost of recycled aggregate is the sum of the production costs of the recycling plant and the SLF.

Recycling Plant The production cost of the recycling plant is the sum of the following items: depreciation, write-off of set-up costs, maintenance and repair, labor, fuel and lubrication, overhead, interest and insurance.

Depreciation cost is based on the economic life of the purchased equipment, economic life being defined as the number of operating hours the equipment can service before becoming functionally obsolete. We have assumed a straight line depreciation method and an economic life of 15,000 hours. Accordingly, the depreciation cost of equipment equals the purchasing cost of equipment over 15,000 hours. An estimate of the depreciation cost of the various designed plants appears in Table 18, Col. 5.

The write-off of set-up costs will be based either on the economic life of equipment or on the number of years the plant will be in operation in the specific location, whichever is less. In this work, the latter, being no more than 5 years (Tables 24 to 33) is always less than the assumed life of equipment which is 7.5 years (or 15,000 hours). We have assumed a straight line depreciation method; accordingly, the write-off of set-up costs, in \$/yr, will equal the amount of set-up costs over the number of years the plant will be in operation in the specific location. To convert the above cost of dollars per year to dollars per hour one has to make an assumption about the number of hours the plant operates each year. For a yearly operation of 1000 hours and a plant that will be in operation for 4 years in the disaster area, the write-off of set-up costs can be found in Table 18, Col. 6.

The maintenance and repair cost of the recycling system is estimated to be 90% of the depreciation cost (Table 18, Col. 7).

Labor costs are presented in Col. 8 of Table 18 and have been derived from Table 20; the latter shows labor requirements in each plant and labor wages. We have assumed that the administrative work is done by the crusher operator.

The fuel cost for equipment powered by the central power unit (see Tables 12 to 15) has been calculated as follows: we have summed up the horsepower requirements of the individual machines (Tables 12 to 15); multiplied the sum with a load factor of 0.8 to convert it to kw and have multiplied the latter by the fuel cost per unit power generated in \$/kw/hr.

The fuel cost per unit power generated varies with the size of the unit. For a 375 kw power unit, the fuel cost to generate one unit of power is \$0.04/kw/hr. For a 500 kw power unit, the fuel cost to generate one unit of power is \$0.036/kw/hr. These cost figures are based on a fuel consumption of 24 gallons/hr and 40 gallons/hr for the 375 kw and 500 kw power units, respectively, and on the current diesel fuel cost of \$0.45/gallon (36).

Lubrication cost for equipment powered by the central power unit has been estimated to be 25% of the fuel cost (12).

The sum of fuel and lubrication costs of individually powered equipment appears in Tables 12 to 15.

The total fuel and lubrication cost of all equipment (individually and centrally powered) for all designed plants appears in Table 18, Col. 9.

We have assumed that overhead cost, in \$/year, is equal to 1/2% of initial investment (Table 18, Col. 10). To convert the above cost in \$/hr one has to make an assumption on the number of hours the plant was in operation during the year. Overhead costs in \$/hr for the various designed plants at different operating hours per year appear in Table 21. It can be seen from this Table that the overhead cost, in \$/hr, significantly decreases as the hours of plant operation each year increases. For a plant operating 1000 hours a year, the overhead cost, in \$/hr, can be found in Table 18, Col. 11.

We have assumed that the interest charge is 9% and the insurance charge is an additional 1% of initial investment. The total hourly cost for these charges has been determined from Fig. 18. The latter provides us with a multiplier factor as a function of the sum of the two rates above and hours of plant operation each year. The hourly cost is then obtained as follows (22):

> Hourly cost for interest and insurance = Multiplier Factor x Delivered Price of Equipment/1000.

The hourly interest and insurance cost for the 4 designed plants and for different hours of operation each year appear in Table 22. It can be seen from this Table that the insurance and interest cost drops significantly as the number of hours of operation increases. For a plant operating 1000 hours a year the interest and insurance charges can be found in Table 18, Col. 12.

The production cost of the designed recycling plants, exclusive of depreciation and write-off costs, appears in Table 23 for various levels of hours of annual operation. Once again the significant impact of the number of hours of operation on production cost can be seen.

The total production cost, in \$/hr, of a recycling plant operating 1000 hours a year for 4 years appears in Table 18, Col. 13. For plants operating at average capacity each hour, this cost has been converted in $/ton in Col. 14 of the same Table and has been plotted in Fig. 19 as a function of plant capacity. It can be clearly seen that there are economies of scale in the production cost of recycled aggregate.

SLF We have called production cost of the SLF system the sum of the following costs: labor; maintenance, repairs, fuel and lubrication of equipment; purchase and hauling of cover material; administrative services; utilities; insurance; facilities maintenance.

A plot of the production cost in dollars per ton of debris that is stored at the SLF has been adopted from Ref. 22 and appears in Fig. 20. As the fill rate increases, production cost sharply decreases for small fill rates, but levels off at high fill rates. The actual production costs at the designed SLF has been obtained from Fig. 20 and appears in line 3.2 of Tables 24 to 34.

The production cost described above has not taken into account the rental cost of scrapers, the depreciation cost of the facilities and set-up and the annual property tax.

The rental cost of scrapers appears in line 3.3 of Tables 24 to 34. The number of scrapers required depends on the daily fill rate of the SLF (line 1.6, Tables 24 to 34). It is assumed in this work that one scraper is required for every 400 tons of fill per day of operation. The rental cost of an 11 cu yd capacity self loading scraper is $2910 per month.

All items of initial investment with the exception of land are depreciable. We have assumed a straight line depreciation over the investment period at the SLF. The estimated charges appear in line 3.4 of Tables 24 to 34.

Finally, we have assumed a 7.5% annual property tax on the value of land and facilities. The value of land and facilities has been obtained from Table 19; the resulting tax appears in line 3.5 of Tables 24 to 34.

5.3 ANNUAL INCOME STATEMENTS OF RECYCLING SYSTEMS

In this work we have studied promising systems (combinations) of recycling plants at SLF's that will process the concrete debris generated by a natural disaster. These combinations are described in Tables 24 to 34 from which it can be seen that depending on the quantities of debris produced one or two recycling plants of different capacities, adjacent to SLF's are established. Each of these plants is in operation in the disaster area for different lengths of time. The latter varies from a minimum of 2 to a maximum of 5 years.

The annual statement of income of all combinations studied appear in Part IV of Tables 24 to 34. Revenue is generated from three sources:
a) Sale of recycled aggregate. We have assumed that 100% of processed aggregate will be sold. The sale price is $1.67 ton. This is the actual price at which recycled concrete sells at Los Angeles (52). Furthermore, it is the coarse aggregate price that will yield a recycled aggregate concrete of the same cost as natural aggregate concrete when both types of concrete have the same properties and the quarry price of natural aggregate is $3.30/ton.

Based on the above assumptions, the total annual revenue from the sale of aggregate equals $1.67/ton times the tonnage of concrete aggregate produced (line 4.1, Tables 24 to 34).
b) Sale of re-bars. We have assumed that the revenue from the sale of rebars amounts to $0.25 per ton of concrete debris processed (22). Therefore, the total revenue generated from this source each year is: $0.25/ton times the tonnage of concrete aggregate produced (line 4.2, Tables 24 to 34).
c) Dumping charges. Dumping charges at the recycling plant-SLF combinations are so set as to attract dumping of concrete debris while at the same time discouraging dumping of non-concrete debris. The prevailing dumping charges are $2.00/ton for inorganic waste and $4.50/ton for organic waste (22). In order to achieve the stated objectives, we have adopted the following charging system: dumping of concrete debris is free; $5.00/ton is charged for the dumping of non-concrete debris.

It follows that the annual revenue from dumping charges is: $5.00/ton times the tonnage of non-concrete debris dumped in the SLF during the year (line 4.3 of Tables 24 to 34).

Annual expenses at the recycling plant-SLF system are the following:
a) production cost of the recycling plant (line 4.4, Tables 24 to 34);
b) total production cost, including depreciation and write-off costs, rental cost of scrapers and property taxes, of the SLF (line 4.6, Tables 24 to 34).

The difference between the sum totals of the above revenues and expenses is operating income. A 50% income charge is imposed on the latter so that net income is the remaining 50% of the operating income (line 4.11, Tables 24-34).

All plant combinations analyzed in this study have a positive net income (profit). This fact alone, however, insufficiently justifies investment in this type of operation.

5.4 ATTRACTIVENESS OF INVESTING IN THE RECYCLING SYSTEMS

To investigate whether the profit derived in the previous section is satisfactory when investment requirements and other investment opportunities are taken into account, a net present value analysis was performed. To this end the cash flow of the recycling systems was estimated in Part V of Tables 24 to 34 as follows:

Cash outflow in any year includes capital investment (if any), the production cost of the recycling plant(s), excluding depreciation and write-off of set-up costs (line 2.11, Tables 24 to 34) and the total production cost of the SLF(s) including property tax and rental cost of equipment and excluding depreciation.

All cash outflow for capital investment occurred in the beginning of operations and equalled the sum total of investment in the recycling plant(s) and SLF(s).

Depreciation and write-off charges have been consistently excluded from cash outflows, since they do not represent actual cash payments.

Cash inflow in any year includes sale of capital (if any) operating revenues and a tax shield which is 50% of total depreciation.

All sale of capital took place at the end of the investment period and involved sale of equipment and the SLF land. The salvage value of plant(s) was assumed to be equal to the difference between the pruchasing cost and "accumulated" depreciation cost of equipment (line 2.12, Tables 24 to 34). At the same time the SLF area, after having been completely filled with refuse material and properly treated, is assumed to have been sold at $15,000/acre. This is $5,000/acre more than the original price and is subject to a 30% capital gain tax. Therefore, the net receipt from the sale of land was 70% of the profit plus the original purchasing price of land. All other facilities and assets at the SLF are assumed to have zero salvage value at the end of the investment period (line 3.6, Tables 24 to 34).

All cash flows were discounted by 15% to get their present values (line 5.7, Tables 24 to 34) and the algebraic sum of all present values gives the net present value of investment. The latter was negative in one instance only: when the total quantity of debris produced by the natural disaster was only 0.5 million tons (line 5.8, Table 24 and Table 35). In this case recycling operations generated a return of less than 15%. In all other cases - where the natural disaster produced at least 1 million tons of concrete debris - the recycling systems generated a return higher than 15% (the net present value was positive - line 5.8, Tables 25 to 34 and Table 35).

We have asked the question on the attractiveness of investment in a recycling system in still another way: what is the rate of earning at which the present value of the earnings equals the amount of investment? This earnings rate is called internal rate of return and has been estimated for all 11 recycling systems in Table 35. It can be seen that in cases where the natural disaster has generated at least 1 million tons of concrete debris recycling systems have generated an internal rate of return of at least 19% and as high as 47%. That is, investment in these recycling systems is very attractive.

5.5 COMPARISON OF RECYCLED AGGREGATE CONCRETE AND NATURAL AGGREGATE CONCRETE

In previous sections the implicit assumption has been made that the recycled aggregate producer will be able to sell 100% of his product. For this assumption to be correct, recycled aggregate must compare favorably with its competitor, natural aggregate.

A fair comparison between the two types of aggregate would involve comparison of two concrete members of equal performance, one made with recycled and the other made with natural aggregate. To compensate for the reduced strength (see Cahpter 2 of this report) the member using recycled aggregate would have to have a 10% higher cement content.

To assist in derivation of specific numbers, Table 34 contains the material composition of 1 cu yd of natural aggregate concrete and that of an equal performance recycled aggregate concrete. The only difference in material quantities between the above two types of concrete is the higher cement content of RAC. We have made the assumption that natural coarse aggregate is available at the market site and that the same is true for recycled aggregate. Under these assumptions and for a price of $3.30/ton for the natural aggregate, recycled aggregate should sell for $1.67/ton in order to yield concrete of equal cost and performance (Table 36). In other words, when there is no transportation advantage of either aggregate, an unprejudiced person would be indifferent between natural aggregate that sells for $3.30/ton and recycled aggregate that sells for $1.67/ton.

However, there are good reasons why a person can be prejudiced against recycled concrete. For one, experience with it is limited; secondly, there are no design aids for recycled aggregate similar to the design aids (for instance in the form of Tables of properties) that exist for natural aggregate.

For these reasons, recycled aggregate would sell best in cases where there is a cost advantage in its favor, and this can happen in cases where economies of scale are realized (Fig. 19 and Table 35) so that recycled aggregate can sell for less than $1.67/ton, or in cases where there is a transportation advantage in favor of recycled aggregate.

When recycled aggregate sells for less than $1.67/ton it is economically more attractive than natural aggregate even if the latter is locally available. In cases where natural aggregate is not locally available -- and this is the case with many metropolitan areas - there is a transportation advantage in favor of recycled aggregate which makes it economically more attractive than natural aggregate even if recycled aggregate sells at $1.67/ton. Transportation cost for aggregate is 6¢/ton/mile. Therefore, if a quarry for natural aggregate is, for instance, 15 miles further away from the market than a recycling plant, then RAC will be 8% less expensive than an equal performance natural aggregate concrete (Table 36)

In conclusion, following a natural disaster, recycled aggregate will be in great demand, a) in areas where natural aggregate is locally unavailable; b) in areas where natural aggregate, even though available, insufficiently meets the large post-disaster demand; and c) in areas where the quantities of concrete debris produced by the natural disaster are large enough to permit economies of scale and therefore prices of less than $1.67/ton for the recycled aggregate.

5.6 CONCLUSIONS ON THE ECONOMIC FEASIBILITY OF CONCRETE RECYCLING

There are economies of scale in the production cost of the recycling plant and the SLF.

When 1 or more million tons of concrete debris are produced by the natural disaster, investment in a recycling system to process this debris is attractive. As the scale of operations increases, so does the attractiveness of investment. When more than 5 million tons of concrete are produced in the catastrophic event then the generated return on investment in a recycling system is at least 45%.

The above conclusions are based on the assumption that recycled aggregate sells at the price of $1.67/ton which yields a recycled aggregate concrete of equal cost with a natural aggregate concrete of the same performance. The attractiveness of recycled aggregate vis a vis natural aggregate will be enhanced when either recycled aggregate sells for less than $1.67/ton or natural aggregate is locally unavailable. The former can happen at large scale operations where economies of scale are realized and the producer can reduce the price of his product while still realizing substantial profits. The latter is often presently the case in metropolitan areas and can certainly be the case in the disaster area, especially in the reconstruction period when demand for materials is strong.

CHAPTER 6

CONCLUSIONS

Concrete is the most popular construction material and the most abundant one in demolition debris: it accounts for 67% by weight of demolition wastes. Immense quantities of concrete debris are produced in a natural disaster. For instance, in the San Fernando earthquake of 1971, 5 million tons of concrete debris were produced. There are about 200 major disasters in this country per decade (19) which means that the tonnage of concrete debris produced from disasters is of the order of a billion tons per decade and a hundred million tons per year. These mountains of debris can be dumped or they can be recycled.

Technologically speaking, concrete debris, free from contaminants, is a satisfactory substitute for coarse aggregate in the production of new concrete. Recycled aggregate concrete has lower strength than natural aggregate concrete of the same composition, however, the mix composition can be manipulated (for instance, through an increase of the cement content) to produce recycled aggregate concrete of the same strength as natural aggregate concrete. The above conclusions are supported both by experimental work and field experience: in a recent highway project the demolished concrete pavement has been recycled as aggregate for the new concrete pavement (41).

Most concrete debris is contaminated with gypsum, wood, plastics, glass, etc. Fortunately, the existing technology of the natural aggregate industry (aggregate beneficiation processes) can adequately eliminate detrimental concrete contaminants.

Recycling plants of large capacity (up to 750 TPH) can be totally based on standard, widely used equipment. Along these lines 14 concrete recycling plants of small to medium capacity are presently in operation. These are mostly portable plants quickly assembled at the site of debris accumulation.

In terms of economics, recycling of concrete debris following a major disaster is indeed attractive. We have made an estimate of the return on investment based on the assumption that recycled aggregate sells at a price that would yield a recycled concrete of the same cost with an equal performance natural aggregate concrete. We found that in cases where a natural disaster will produce one or more million tons of concrete debris, the recycling operations will yield a return of at least 19%. As the quantities of debris increases, so does the return on investment of the recycling operations. When the debris produced by the catastrophic event amounts to 7 million tons, recycling operations yield the lucrative return of 47%.

Are consumers willing to buy recycled concrete? At the price of $1.67/ton for recycled aggregate - vis a vis a price of $3.30/ton for natural aggregate - an unbiased consumer will be indifferent between recycled and natural aggregate, since in either case the final product, concrete, will cost the same and will perform identically as construction material. Even in the presence of consumers who may be biased against it, however, prospects for recycled aggregate sales are good because the economics in several cases are in favor of the recycled product. For instance, natural aggregate is locally unavailable in several areas to the point where recent research is focusing on exotic solutions, such as digging aggregate from the ocean floor (44). In all these cases, there is a significant transportation advantage in favor of recycled aggregate. Even where natural aggregate is locally available there might not be large enough quantities to meet the sudden increase in demand following reconstruction. Furthermore, the potential returns realized at high levels of recycling operations are so large that recycled aggregate producers can afford to lower their prices to undersell their competitors (natural aggregate producers) while still realizing significant savings.

We can trace the above in our study of the San Fernando earthquake of 1971. In the San Fernando area natural aggregate is locally unavailable. Most of the aggregate used requires one-way truck hauls of up to 50 miles (52). For this reason, several of the recycling plants that presently exist are located in this area. Following the 1971 earthquake the impressive mass of 5×10^6 million tons of concrete debris has been dumped. The alternative would have been to recycle the above debris as concrete aggregate that would yield concrete of no inferior quality than natural aggregate concrete, that would save millions of dollars to consumers and grant a 45% return on investment to producers.

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TABLE 1. - Compressive Strength of the Recycled Specimens and of Controls

Type of Specimen	Age Days	Compressive Strength (psi)							
		Portland Cement Type I				Portland Cement Type II			
		water to cement ratio				water to cement ratio			
		0.45	0.55	0.65	0.75	0.45	0.55	0.65	0.75
Control	14	4750±320	3680±310	2580±255	1855±305	4746±160	3620±329	2500±210	1850±357
	28	4980±580	4150±480	3125±345	2520±270	4900±678	4080±146	3120±410	2300±215
	49	5355±450	4820±508	3790±407	2390±110	5260±555	4560±398	3680±400	2180±235
Uncontaminated RAC	14	4510±425	3485±405	2380±225	1590±125	3780±135	2640±475	2085±110	1425±110
	28	4385±360	3910±108	2570±58	1790±221	4070±150	3860±352	2505±230	1795±283
	49	5260±310	4220±135	2537±65	2200±180	4840±509	4010±580	2960±305	2190±140
Contaminated RAC	14	2630±458	1790±334	1660±182	990±106	3330±296	2340±280	1880±175	1470±110
	28	3480±542	2700±698	2050±206	1290±51	3510±520	3480±220	2470±80	1580±124
	49	3620±537	2710±160	2100±84	1610±16	3680±474	3790±134	2680±88	2310±264
Gypsum-Mortar	14		780±180		706±82		706±45		680±75
	28		1160±61		850±65		1100±130		1060±71
	49		940±160		990±77		950±160		940±159

TABLE 2. - Volume Changes of Concrete* Cylinders Stored in Water

Type of Specimen	Amount of Gypsum in the Mix		Age Days	Volume Changes (Expansion) of Co Cylinders Stored Continuously in Percent of one-day volume	
	Gypsum - % by weight of cement	Calculated as SO_3 - % by weight of cement		Specimens produced with Portland Cement Type I	Specimens pr with Portland Cement Type II
Uncontaminated Gypsum	0	0	14	0.03±0.12	0.05±0.08
			28	0.15±0.13	0.14±0.14
			49	0.14±0.16	0.16±0.12
Contaminated Gypsum	15	7	14	0.04±0.15	0.04±0.22
			28	0.90±0.08	0.14±0.13
			49	0.31±0.25	0.27±0.14
Gypsum-Mortar	225	105	14	0.82±0.24	0.55±0.19
			28	1.00±0.21	0.69±0.13
			49	1.18±0.21	0.72±0.18

*The water to cement ratio was kept constant at 0.55.

TABLE 3. - Consistency of the Recycled Specimens and Their Controls.

Type of Specimen	Slump* (inches)							
	Portland Cement Type I				Portland Cement Type II			
	water to cement ratio				water to cement ratio			
	0.45	0.55	0.65	0.75	0.45	0.55	0.65	0.75
Control	0.42±0.12	1.62±0.16	3.29±0.21	3.75±0.10	0.38±0.17	1.58±0.21	3.32±0.67	3.45±0.36
Uncontaminated RAC	0.26±0.10	1.45±0.38	3.38±0.45	3.75±0.20	0.25±0.10	1.42±0.20	2.88±0.43	3.25±0.25
Contaminated RAC	0.20±0.15	1.20±0.30	3.17±0.42	3.67±0.18	0.18±0.10	1.21±0.25	3.25±0.10	3.62±0.17
Gypsum Mortar		0.15±0.10		0.75±0.20		0.25±0.12		0.88±0.30

*Measured on a 6 in cone.

TABLE 2. - Volume Changes of Concrete* Cylinders Stored in Water

Type of Specimen	Amount of Gypsum in the Mix		Age Days	Volume Changes (Expansion) of Concrete Cylinders Stored Continuously in Water Percent of one-day volume	
	Gypsum - % by weight of cement	Calculated as SO_3 - % by weight of cement		Specimens produced with Portland Cement Type I	Specimens produced with Portland Cement Type II
Uncontaminated Gypsum	0	0	14 28 49	0.03±0.12 0.15±0.13 0.14±0.16	0.05±0.08 0.14±0.14 0.16±0.12
Contaminated Gypsum	15	7	14 28 49	0.04±0.15 0.90±0.08 0.31±0.25	0.04±0.22 0.14±0.13 0.27±0.14
Gypsum-Mortar	225	105	14 28 49	0.82±0.24 1.00±0.21 1.18±0.21	0.55±0.19 0.69±0.13 0.72±0.18

*The water to cement ratio was kept constant at 0.55.

TABLE 4 - Comparison of Properties of Uncontaminated Recycled Aggregate Concrete and Natural Aggregate Concrete of Similar Composition

Type of Property	Uncontaminated RAC
Compressive Strength	65 to 100% of Control (Ref. 4,16,18,27 39 and Table 1)
Static Modulus of Elasticity in Compression	60 to 100% of Control (Ref. 16 and Fig. 3)
Flexural Strength	80 to 100% of Control (Ref. 27)
Linear Coefficient of Thermal Expansion	Comparable to that of Control (Ref. 4)
Length Changes of Concrete Specimens Stored for 28 Days at 90% R.H. and 73°F	Comparable to that of Control (Ref. 4)
Freeze-thaw Resistance	Comparable to that of Control (Ref. 4, 27)
Slump	Comparable to that of Control (Ref. 4,16, 27 & Table 3)

TABLE 5 - Damage Probability Matrix for Buildings* (54)

Design Strategy	Damage State	Percent of Total Square Footage in Each Damage State					
		Earthquake Intensity on the Modified Mercalli Scale					
		V	VI	VII	VIII	IX	X
UBC** 0, 1	None	100	27	15	0	0	0
	Light	0	73	48	0	0	0
	Moderate	0	0	33	20	0	0
	Heavy	0	0	4	41	0	0
	Total	0	0	0	39	100	100
UBC** 2	None	100	47	20	0	0	0
	Light	0	53	50	10	0	0
	Moderate	0	0	29	53	0	0
	Heavy	0	0	1	31	0	0
	Total	0	0	0	6	100	100
UBC** 3	None	100	57	25	0	0	0
	Light	0	43	50	25	0	0
	Moderate	0	0	25	53	20	0
	Heavy	0	0	0	21	52	0
	Total	0	0	0	1	28	100

* The matrix is applicable to non-wooden construction only.

** Uniform Building Code (UBC) seismic zoning 0, 1, 2 or 3.

TABLE 6 - Definition of Damage States for Buildings and Concrete Debris Generation

Damage State* (1)	Verbal Description* (2)	Damage Ratio = Cost of Repairing Over Cost of Replacement % (3)	Structural Concrete That Needs Replacement % (4)	Concrete Debris Generated tons/sq.ft. (5)=(4)x0.06
None	No damage.	0	-	-
Light	Minor or localized non-structural damage. A few walls and partitions cracked. Incidental mechanical and electrical damage.	0.3	-	-
Moderate	Widespread non-structural damage. Possibly some structural damage with obvious cracking or yielding in some structural members.	5	-	-
Heavy	Major structural damage requiring repair or replacement of many structural members. Associated non-structural damage requiring repairs of major portion of interior. Building vacated during repairs.	30	11	0.0065
Total	Building condemned or collapsed.	100	100	0.06

* After Reference (54).

TABLE 7 - Definition of Damage States for Highways and Concrete Debris Generation.

Damage State (1)	Verbal Description (2)	Concrete That Needs Replacement % (3)	Concrete Debris Generated tons/mile $(4)=(3)\times 6600\ \frac{\text{tons}}{\text{mile}}$*
Minor	None or insignificant movement of the highway segment** as a whole; minor cracking and displacement of pavement slabs in roadway segment; some cracking and spalling of concrete piers in bridge segment.	0	0
Moderate	Minor differential settlement or lateral displacement relative to adjacent highway segments as a whole; significant cracking and displacement of pavement slabs in roadway segment; some structural damage in bridge segment.	10	660
Heavy	Significant differential settlement or lateral displacement relative to adjacent highway segments, extensive cracking and displacement of pavement slab in roadway segments; collapse or severe structural damage in bridge segment.***	100	6600

* 6600 tons of concrete are used per highway mile (22).

** The term "highway segment" as used here refers to highway segments of quite uniform characteristics, e.g., a roadway segment that has uniform slope or curvature, or a single bridge overpass.

*** Heavy damage preferentially occurs at the bridge-embankment junctions, in locations where heavy landslides occur and in route interchanges.

TABLE 8 - Concrete Debris from Buildings:
San Fernando Earthquake of 1971.

Type of Building Construction and Damage State (1)	Number of Damaged Buildings* (2)	Average Square Footage of Damaged Buildings (3)	Total Damaged Square Footage (4)=(2)x(3)	Concrete Debris Generated, tons/sq.ft.** (5)	Total Amount of Concrete Debris Generated, tons (6)=(4)x(5)
Residential Space Totally Damaged	65	90200	5.86×10^6	0.06	0.3516×10^6
Residential Space Heavily Damaged	265	90200	23.9×10^6	0.0066	0.1577×10^6
Non-Residential Space Totally Damaged	574	106600	61.19×10^6	0.06	3.7114×10^6
Non-Residential Space Heavily Damaged	1125	106600	119.92×10^6	0.0066	0.7915×10^6
				TOTAL	5.0122×10^6

* After Ref. 3.
** From Table 6, Col. 5.

TABLE 9 - Rapid Estimate of Building Square Footage Damaged in the San Fernando Earthquake of 1971

Modified Mercalli Intensity (1)	Urban Area Affected* (sq. miles) (2)	Distance of Center of Affected Area From the Center of Los Angeles* (miles) (3)	RESIDENTIAL CONSTRUCTION			
			Non-wood Frame Density at the Center of Affected Area** (sq. ft./sq. mi.) (4)	Total Square Footage Affected (5)=(2)x(4)	Sq. Footage Designed According to UBC, 0*** $(6)=\frac{1}{3}(5)$	Sq. Footage Designed According to UBC 3*** $(7)=\frac{2}{3}(5)$
IX	13	22	0.23×10^6	2.99×10^6	1.0×10^6	1.99×10^6
VIII	69	17	0.52×10^6	35.88×10^6	11.96×10^6	23.92×10^6
VII	437	5	0.65×10^6	284.05×10^6	94.68×10^6	189.37×10^6

* From Fig. 6.
** From Ref. 47.
*** From Ref. 53.

TABLE 9 - Continued

RESIDENTIAL CONSTRUCTION		NON-RESIDENTIAL CONSTRUCTION		
Sq. Footage Totally Damaged**** (8)	Sq. Footage Heavily Damaged**** (9)	Non-wood Frame Density at the Center of Affected Area** (sq. ft./sq. mile) (10)	Total Sq. Footage Affected (11)=(2)x(10)	Sq. Footage Designed According To UBC 0*** $(12)=\frac{1}{3}(11)$
100%(6) + 28%(7) = 1.55 x 10^6	0 x (6) + 52%(7) = 1.03 x 10^6	3.93 x 10^6	51.09 x 10^6	17.03 x 10^6
39%(6) + 1%(7) = 4.90 x 10^6	41%(6) + 21%(7) = 9.79 x 10^6	6.20 x 10^6	367.72 x 10^6	122.57 x 10^6
0	4%(6) + 0%(7) = 3.79 x 10^6	7.85 x 10^6	3430.45 x 10^6	1143.48 x 10^6
TOTAL 6.45 x 10^6	14.61 x 10^6			

****Percentages taken from Table 5.

TABLE 9 - Continued

NON-RESIDENTIAL CONSTRUCTION		
Sq. Footage Designed According to UBC, 3*** (13) = $\frac{2}{3}$(11)	Sq. Footage Totally Damaged**** (14)	Sq. Footage Heavily Damaged**** (15)
34.06×10^6	100%(12) + 28%(13) = 23.16×10^6	0 + 52%(13) = 17.71×10^6
245.12×10^6	39%(12) + 1%(13) = 50.25×10^6	41%(12) + 21%(13) = 101.73×10^6
2286.97×10^6	0	4%(12) + 0%(13) = 45.74×10^6
	TOTAL 73.41×10^6	165.18×10^6

****Percentages taken from Table 5.

TABLE 9 - Continued

RESIDENTIAL CONSTRUCTION		NON-RESIDENTIAL CONSTRUCTION		
Sq. Footage Totally Damaged**** (8)	Sq. Footage Heavily Damaged**** (9)	Non-wood Frame Density at the Center of Affected Area** (sq. ft./sq. mile) (10)	Total Sq. Footage Affected (11)=(2)x(10)	Sq. Footage Designed According To UBC 0*** $(12)=\frac{1}{3}(11)$
100%(6) + 28%(7) = 1.55×10^6	0 x (6) + 52%(7) = 1.03×10^6	3.93×10^6	51.09×10^6	17.03×10^6
39%(6) + 1%(7) = 4.90×10^6	41%(6) + 21%(7) = 9.79×10^6	6.20×10^6	367.72×10^6	122.57×10^6
0	4%(6) + 0%(7) = 3.79×10^6	7.85×10^6	3430.45×10^6	1143.48×10^6
TOTAL 6.45×10^6	14.61×10^6			

****Percentages taken from Table 5.

TABLE 10 - Rapid Estimate of Damaged Space Versus Data-Based Estimate. Comparison of Results.

Type of Building Construction and Damage State	Estimate Based on Published Data* sq. feet	Rapid Estimate** sq. feet	Difference percent
Residential Space Totally Damaged	5.86×10^6	6.45×10^6	10
Residential Space Heavily Damaged	23.90×10^6	14.61×10^6	39
Non-Residential Space Totally Damaged	61.19×10^6	73.4×10^6	20
Non-Residential Space Heavily Damaged	119.92×10^6	165.18×10^6	38
TOTAL	210.87×10^6	259.65×10^6	18

* After Table 8.
** After Table 9.

TABLE 11 - Processable Quantities of Concrete Debris Each Year.

Total Quantity of Concrete Debris Produced by Natural Disaster (million tons)	Processable Quantities of Concrete Debris (million tons/year)					
	Year of Plant Operation					
	1	2	3	4	5	6
0.5	0.1389	0.1111	0.0833	0.0556	0.0278	0.0034
1	0.2778	0.2222	0.1667	0.1111	0.0556	0.0069
2	0.5556	0.4444	0.3333	0.2222	0.1111	0.0138
3	0.8333	0.6667	0.5000	0.3333	0.1667	0.0208
4	1.1111	0.8889	0.6667	0.4444	0.2222	0.02778
5	1.3889	1.1111	0.8333	0.5556	0.2778	0.0347
6	1.6667	1.3333	1.0000	0.6667	0.3333	0.0416
7	1.9444	1.5556	1.1662	0.7778	0.3889	0.0486
8	2.2222	1.7778	1.3222	0.8889	0.4444	0.0556
9	2.5000	2.0000	1.5000	1.0000	0.5000	0.0625
10	2.7778	2.2222	1.6667	1.1111	0.5555	0.0694

TABLE 12 - Equipment for a Recycling Plant of 120 to 300 TPH Capacity.

Equipment	Quantity	Estimated Purchase Price 1977 (in dollars)	Average Horsepower Requirements
1. 42" x 16' hopper-feeder	1	100,000	20
2. 5' x 14' single-deck screen (4" openings)	1	35,000	30
3. 30"x42" jaw crusher (discharge 4"; max feed ≈ 2'x2'; capacity: 200 TPH)	1	91,600	150
4. 42" x 50' belt conveyor (spring type)	1	20,000	25
5. magnetic separator	1	11,500	14
6. 44" x 20' double-screw washer (max. feed = 4"; capacity: 400 TPH)	1	37,300	20
7. 5' x 16' triple-deck screen (openings: 1½ ", 3/4", 3/8")	1	57,000	30
8. 5100 short-head cone crusher (discharge 1"; max. feed ≈ 5½" capacity: 200 TPH)	1	130,000	175
9. 24" x 60' recirculating belt conveyor	1	12,000	10
10. 24" x 50' radial stacker	3	10,000 @	10 @
	Subtotal:	524,400	504
			Fuel & Lubrication Costs ($/hour)
11. 500 kw power unit	1	13,000	
12. 6" diameter pump and piping	1	3,000	1.60
13. 5½" cu. yard front-end loader	1	93,250	16.70
14. 105 HP bulldozer	1	54,700	3.08
15. backhoe with hydraulic hammer	1	57,000	6.33
	Subtotal	280,950	27.71
	TOTAL	805,350	

Note: Equipment 1 - 10 is centrally powered.
Equipment 11 - 15 is individually powered.
Equipment 1 - 12 requires setting up.

TABLE 13 - Equipment for a Recycling Plant of 300 to 450 TPH Capacity.

	Equipment	Quantity	Estimated Purchase Price 1977 (in dollars)	Average Horsepower Requirements
1.	42" x 16' hopper-feeder	1	100,000	20
2.	6' x 16' single-deck screen (4" openings with perforated plates)	1	65,000	35
3.	24" x 40' belt conveyor	1	8,000	10
4.	42" x 40' belt conveyor	1	10,400	25
5.	30" x 42" jaw crusher (discharge 4"; max. feed ≈ 2'x2'; capacity: 200 TPH)	2	91,600 @	150 @
6.	42" x 50' belt conveyor (spring-type)	2	20,000 @	25 @
7.	magnetic separator	2	11,500 @	14 @
8.	36" x 40' belt conveyor	1	9,600	15
9.	surge pile feeder	1	20,000	20
10.	44" x 20' double-screw washer (max. feed = 4"; capacity: 400 TPH)	1	37,300	20
11.	44" x 70' single-screw washer (max. feed = 4"; capacity: 200 TPH)	1	21,000	40
12.	36" x 40' belt conveyor	1	9,600	15
13.	6' x 16' triple-deck screen (openings: 1½", 3/4", 3/8")	1	60,000	35
14.	66 S cone crusher (discharge: 1¼" max. feed ≈ 8"-11"; capacity: 320 TPH)	1	200,000	225
15.	30" x 60' recirculating belt conveyor	1	13,200	15
16.	24" x 80' radial stacker	3	16,000 @	15 @
		Subtotal	848,300	898

				Fuel & Lubrication Costs ($/hour)
17.	375 kw power unit	2	43,000 @	
18.	6" dia. pump & piping	1	3,000	1.60
19.	4 ½ cu. yard front-end loader	2	93,250 @	16.70 @
20.	105 HP bulldozer	1	54,700	3.08
21.	backhoe with hydraulic hammer	1	57,000	6.33
		Subtotal	387,200	44.41
		TOTAL	1,235,500	

Note: Equipment 1 - 16 is centrally powered.
Equipment 17 to 21 is individually powered.
Equipment 1 to 18 requires setting up.

TABLE 14 - Equipment for a Recycling Plant of 450 to 600 TPH Capacity.

Equipment	Quantity	Estimated Purchase Price/1977 (in dollars)	Average Horsepower Requirements
1. 48" x 20' hopper-feeder	1	122,000	30
2. 6' x 16' single-deck screen (4" openings with perforated plates)	1	65,000	35
3. 24" x 40' belt conveyor	1	8,000	10
4. 42" x 40' belt conveyor	1	10,400	25
5. 30" x 42" jaw crusher (discharge: 4"; max. feed ≈ 2'x2'; capacity: 200 TPH)	2	91,600 @	150 @
6. 42" x 50' belt conveyor (spring-type)	2	20,000 @	25@
7. magnetic separator	2	11,500 @	14 @
8. 42" x 40' belt conveyor	1	10,400	25
9. surge pile feeder	1	20,000	20
10. 44" x 20' double-screw washer (max. feed = 4", capacity: 400 TPH)	2	37,300 @	20 @
11. 42" x 40' belt conveyor	1	10,400	25
12. 7' x 20' triple-deck screen (openings: 1½", 3/4", 3/8")	1	90,000	40
13. 5100 short-head cone crusher (discharge: 1"; max. feed ≈ 5½"; capacity: 200 TPH)	1	130,000	175
14. 66S cone crusher (discharge: 1¼"; max. feed ≈ 8"-11"; capacity: 320 TPH)	1	200,000	225
15. 30" x 100' recirculating belt conveyor	1	22,000	25
16. 24" x 80' radial stacker	3	16,000 @	15 @
	Subtotal	1,057,000	1,098
			Fuel & Lubrication Costs ($/hour)
17. 375 kw power unit	1	43,000	
18. 500 kw power unit	1	73,000	
19. 6" dia. pump & piping	1	3,000	1.60
20. 4½ cubic yard front-end loader	2	93,250 @	16.70 @
21. 26 ton crane-dragline w/5½ cu. yard bucket	1	130,000	4.50
22. 105 HP bulldozer	1	54,700	3.08
23. backhoe w/hydraulic hammer	2	57,000 @	6.33 @
	Subtotal	604,200	55.24
	TOTAL	1,661,200	

Note: Equipment 1-16 is centrally powered.
Equipment 17 - 23 is individually powered.
Equipment 1 - 18 requires setting up.

TABLE 15 - Equipment for a Recycling Plant of 600 to 750 TPH Capacity

	Equipment	Quantity	Estimated Purchase Price/1977 (in dollars)	Average Horsepower Requirements
1.	48" x 20' hopper-feeder	1	122,000	30
2.	6' x 16' double-deck screen (openings: 8" and 4", with perforated plates)	1	70,000	35
3.	24" x 40' belt conveyor	1	8,000	10
4.	42" x 40' belt conveyor	1	10,400	25
5.	22" x 50" jaw crusher (discharge: 4"; max. feed ≈ 1'x1'; capacity: 230 TPH)	1	120,000	125
6.	42" x 48" jaw crusher (discharge: 4"; max. feed ≈ 3'x3'; capacity: 270 TPH)	1	250,000	200
7.	42" x 50' belt conveyor (spring-type)	2	20,000 @	25 @
8.	magnetic separator	2	11,500 @	14@
9.	48" x 50' belt conveyor	1	14,000	30
10.	surge pile feeder	2	20,000 @	20 @
11.	44" x 20' double-screw washer (max. feed 4"; capacity: 400 TPH)	2	37,300 @	20 @
12.	48" x 50' belt conveyor	1	14,000	30
13.	7' x 20' triple-deck screen (openings: 1½", 3/4", 3/8")	1	90,000	40
14.	5100 short-head cone crusher (discharge: 1"; max. feed ≈ 5½"; capacity: 200 TPH)	1	130,000	175
15.	66S cone crusher (discharge: 1¼"; max. feed ≈ 8"-11"; capacity: 320 TPH)	1	200,000	225
16.	36" x 100' recirculating belt conveyor	1	24,000	25
17.	24" x 100' radial stacker	3	20,000 @	15 @
		Subtotal	1,290,000	1,153
				Fuel & Lubrication Costs ($/hour)
18.	500 kw power unit	2	73,000 @	
19.	6" dia. pump & piping	1	3,000	1.60
20.	4½ cu. yd. front-end loader	2	93,250 @	16.70 @
21.	26 ton crane-dragline with 5½ cu. yd. bucket	1	130,000	4.50
22.	105 HP bulldozer	2	54,700 @	3.08 @
23.	backhoe w/hydraulic hammer	2	57,000 @	6.33 @
		Subtotal	688,900	58.32
		TOTAL	1,978,900	

Note: Equipment 1 - 17 is centrally powered.
Equipment 18 - 23 is individually powered.
Equipment 1 - 19 requires setting up.

TABLE 16 - Concrete Recycling Plants. Current Practice (52)

	Plant Owner and Location		
	Shamrock Processed Base Co. Los Angeles, CA	Guy F. Atkinson Co. Pacoima, CA	Blue Diamond Div. of Sully Miller Long Beach, CA
Years Operated		1971	Since 1963
Materials Recycled	Concrete and asphalt from pavements, foundations, curbs & gutters, sidewalks etc.	Concrete and asphalt from streets & sidewalks	Concrete & asphalt from streets, curbs, & gutters, sidewalks
Applications for the Recycled Materials	Base for roadways (99%) Cement slurry backfall (1%)	Base for roadways	Base for roadways
Description of the Plant(s)	Front end loader → Cedar Rapids 40' apron feeder → Cedar Rapids 2540 jaw → Symons 4x16 screen → Symons 4½' cone Portable Front end loader → Cedar Rapids 14' apron feeder → Cedar Rapids 2236 jaw → Symons 4x16 screen → Symons 4' cone Portable	Front end loader → Kohlman belt conveyor → Telsmith 3042 jaw → Telsmith cone Produced minus 3/4" aggr.	Front end loader → Cedar Rapids 2540 jaw portable plant, incl. feeder → Cedar Rapids port. screening unit → 4' Telsmith cone - Portable, produces minus 1" to minus 1½" Front end loader → Cedar Rapids 3242 jaw port. plant → 4½' Symons cone Portable, produces minus 1½"
Production Rate	225 to 250 TPH	300 TPH	
Plant Advantage	Reduced trucking costs		Reduced trucking costs
Problems			
Reasons for Discontinuation of Operations		When their equipment became tied up with other projects not involving rubble, they decided it was cheaper to sub-contract rubble crushing than to utilize their own equipment.	

TABLE 16 - Continued

	Plant Owner and Location		
	Motor Grader Rentals Bell Gardens, CA	Ken H. Jones & Co. Torrance, CA	R & O Portable Crushing Arcadia, CA
Years Operated	Since 1970	Since 1970	Since 1973
Materials Recycled	Concrete and asphalt from pavements, curbs and gutters, building foundations, etc.	Concrete and asphalt from pavements, curbs and gutters, building foundations, etc.	Concrete and asphalt from roads, curbs and gutters, sidewalks, concrete buildings, bridges.
Applications for the Recycled Materials	Base for roadways, pipe bedding	Subbase for roadways	Base for roadways, sanitary landfill material
Description of of the Plant(s)	Front end loader → Aggregate Systems Inc. feeder → 3042 Universal portable jaw → Hewitt Robins 2 deck 5x16 portable screen → 4' Std. Symons cone - Portable, 2 chasses, produces 3/4" to 1/2"	Front end loader → Lippman 3036 jaw → Symons rod deck screen → Pioneer 5x14 vibrating screen → Symons 4' std. cone → Symons 4¼' SH cone Skid mounted, produces sand, 3/8" & 3/4"	Front end loader → Nordberg 3042 jaw → Nordberg 5x16 flat screen → Symons 4¼' cone - Portable, produces minus 1" to minus 1½"
Production Rate	275 TPH	150 TPH	275-375 TPH
Plant Advantage	Reduced trucking costs, reduced manganese costs in the cone crusher	Reduced trucking costs	Reduced trucking costs, reduced dumping costs
Problems			
Reasons for Discontinuation of Operations			

TABLE 16 - Continued

	Plant Owner and Location		
	Strecker Construction Co. Santa Fe Springs, CA	City of Minneapolis (renters) Minneapolis, MN	Texas Highway Department District 17
Years Operated	approx. 1972-1975	Summer of 1972 only	1969
Materials Recycled	Concrete and asphalt	Concrete (sidewalks, etc.) asphalt, clay, dirt	Concrete and asphalt from pavement
Applications for the Recycled Materials	Subbase for roadways	Subbase for roadways, excavation backfill, grillage under sewers, etc., stabilizing material	Asphalt stabilized base course, Type B asphalt surface course
Description of the Plant(s)	Wheel loader → Telsmith Type H vibrating feeder → 30x42 Austin-Western primary jaw → 4x10 Symons 2 deck screen → 489-S Telsmith 4' cone	Loader → Universal 3042 primary jaw → hopper → Telsmith cone → Telsmith vibrating screen → stacker	Primary crusher → conveyor → secondary crusher
Production Rate	350 TPH	200 TPH	
Plant Advantage	Saving of scarce landfill areas, lower cost of resulting roadways, prolonged gravel pit life, reduced demand for trucks	High compaction characteristics of the product, lower truck costs, lower overall costs	Economics
Problems	High maintenance costs on crushing plant, noise pollution from crushing plant, finding sources of rubble, removal of reinforcing steel		
Reasons for Discontinuation of Operations	Plant was sold when the freeway funds were halted.		

TABLE 16 - Continued

	Plant Owner and Location		
	Carl Bolander and Sons 2933 Pleasant Ave. South Minneapolis, Minnesota	Doetsch Brothers Co. 35 E. Palatine Road Wheeling, Illinois	Angelo's Crushed Concrete Detroit, Michigan
Years Operated	At least during 1975	Off & on for several years, to have started up again spring 1976.	Since 1965
Materials Recycled	Concrete and bricks	Concrete	Concrete and asphalt from roadways and sidewalks
Applications for the Recycled Materials	Subbase for raodways	Subbase for roadways, parking lots, haul roads, and for landfill	Base for roadways
Description of the Plant(s)	Front end loader → feeder → 3240 Hewitt Robins Jaw Symons 5100 Std. cone → 6x16 3 deck Nordberg screen → Rexnord portable conveyors	Portable Cedar Rapids 22x 36 jaw plant	They have seven plants. Front end loader → jaw → screens (portable)
Production Rate			
Plant Advantage		Reduced dumping fees by 2/3 by offering crushed vs uncrushed concrete; very competitive with crushed stone from quarries.	Detroit has nearly exhausted its dumping sites for rubble; reduced trucking costs
Problems			
Reasons for Discontinuation of Operations			

TABLE 16 - Continued

	Plant Owner and Location		
	Troy Aggregate Haulers Inc. Troy, Michigan	Michigan Crushed Concrete Rutford, Michigan	Clancy Crushed Concrete Roseville, Michigan
Years Operated	Since 1973	Since 1964	Since 1967
Materials Recycled	Concrete and asphalt from roadways, sidewalks, etc.	Concrete and asphalt pavements, sidewalks, curbs and gutters	Concrete and asphalt from sidewalks and pavements
Applications for the Recycled Materials	Base material for asphalt parking lots	Base material	Base material for roadways
Description of the Plant(s)	Front end loader → Iowa jaw (portable) Front end loader → Universal jaw (stationary)	Front end loader → feeder → 2248 Hewitt Robins jaw → conveyor → magnet → screens → roll crusher	2538 Austin Western jaw (stationary)
Production Rate		190 TPH	38 TPH
Plant Advantage	Detroit has nearly exhausted its dumping sites for rubble	Reduced trucking costs	Crushed stone is scarce in Michigan reduced trucking costs
Problems			
Reasons for Discontinuation of Operations			

TABLE 16 - Continued

	Plant Owner and Location		
	Floyds Crushed Concrete Detroit, Michigan	Silver Hill Sand and Gravel Silver Hill, Maryland	Excavation Construction Washington, D.C.
Years Operated	Since 1962	Since 1968	Since 1972
Materials Recycled	Concrete and asphalt from streets, sidewalks, etc.	Leftover concrete from mixers; curbs and gutters	Concrete from sidewalks, curbs & gutters, streets; they will not accept reinforcing rods
Applications for the Recycled Materials	Base for asphalt roads	Subbase; sewer contractors for haul roads	Subbase
Description of the Plant(s)	Front end loader → 3042 Pioneer primary jaw → double deck screen → 1248 Hewitt Robbins jaw (stationary)	Front end loader → 2438 Iowa jaw	Front end loader → jaw → conveyor → screens (portable)
Production Rate		75 - 100 TPH	100 TPH
Plant Advantage	Reduced trucking costs; many area dumps refuse or charge high dumping fees for uncrushed rubble concrete; shortage of aggregate in Detroit area.		Makes excellent subbase material & is approved by District of Columbia; lower priced material than stone; reduced trucking costs
Problems			
Reasons for Discontinuation of Operations			

TABLE 16 - Continued

	Plant Owner and Location	
	Iowa State Highway Department Ames, Iowa	R.B. Butler, Inc./Jarbet Co./ Texas Hwy. Dpt., Burleson Cty., TX
Years Operated	Start-up expected in Spring, 1976	1967-1969
Materials Recycled	Concrete and asphalt from roadways	Concrete pavement
Applications for the Recycled Materials	Concrete and asphalt combination for 1st layer of concrete pavement; pure concrete for top layer of concrete pavement	Subbase for roadways
Description of the Plant(s)	Portable Iowa Commander plant, including a jaw primary and a roll secondary.	Primary crusher → belt conveyor → secondary crusher
Production Rate		
Plant Advantage		Eliminate disposal problem for rubble concrete pavement Overall costs no more than through use of conventional concepts
Problems		Removal of reinforcing steel from concrete; variable amount of asphalt in the finished rubble; equipment wear was above normal
Reasons for Discontinuation of Operations		

TABLE 17 - Existing Methods of Concrete Cutting (30)

Method of Concrete Cutting	Relevant Property of Concrete	Limitations
Hammer	Poor tensile and impact strength	Slow, noisy, dust
Rotary percussive drill	Poor tensile and impact strength	Only for holes, noisy, dust
Explosive	Poor tensile and impact strength	Lack of precision, dust
Hydraulic bursters in predrilled holes	Poor tensile strength	Slow. Problems with reinforcement
Thermic lance and flame jet	melting point 1200-2000°C	Expensive, fumes and fire hazard
Plasma arc	Melting point 1200-2000°C	Expensive, fumes and fire hazard
Diamond saw	Brittleness	Expensive, difficult on thick sections and where flat survaces are not available

TABLE 18 - Production Cost Estimate for the Recycling Plant

Plant Capacity TPH (1)	Purchase cost of Equipment (after Tables 12 to 15) $ (2)	Set-up Cost (15% of Purchasing Cost of Equipment That Requires Setting Up[1]) (3)	Total Initial Investment (2)+(3) $ (4)	Depreciation Cost of Purchased Equipment (col 2/15,000 hrs) $/hr (5)	Write-off of Set-up Cost for a Plant That Will Operate for 4 Years at 1000 hrs/year (col 3 over 4 years over 1000 hrs) $ (6)	Maintenance & Repair Cost (90% of col 5) $/hr (7)
120-300	805,350	90,060	895,410	53.69	22.515	48.32
300-450	1,235,500	140,595	1,376,095	82.37	35.149	74.13
450-600	1,661,200	176,950	1,837,150	110.75	44.237	99.67
600-750	1,978,900	215,850	2,194,750	131.93	53.962	118.74

[1] With the exception of cranes, bulldozers, loaders and backhoes, all plant equipment requires setting up.

TABLE 18 - Continued

Labor Cost (derived from Table 20) $/hr (8)	Total Fuel & Lubrication Cost $/hr (9)	Overhead (1/2% of col 4) $/yr (10)	Overhead for a Plant Operating 1000 hrs per year $/yr (11)	Interest (9%) & Insurance (1%) for a plant Operating 1000 hrs per year $/hr (12)	Production Cost for a Plant That Will Operate over 4 years at 1000 hrs/yr (5)+(6)+(7)+(8)+(9)+(11)+(12) (13)	Production Cost for a Plant that Will Operate over 4 years at 1000 hrs/yr at Average Capacity (col 13 over av. hourly capacity) $/ton (14)
74.41	45.85	4477.05	4.48	54.61	303.88	1.45
108.75	80.33	6880.48	6.88	84.31	471.92	1.26
123.53	96.96	9185.75	9.18	112.35	596.68	1.14
151.28	104.44	10973.75	10.97	134.22	705.54	1.05

TABLE 19 - Initial Investment in the Sanitary Land Fill System

Total Quantity of Concrete Debris Produced by Natural Disaster (million tons) (1)	Total Quantity of Non-concrete Debris Dumped in the SLF throughout the Life of the Recycling System[1] (sum of quantities in line 1.7 in subsequent Tables 24 to 34) (million tons) (2)	SLF Land Area[2] (acres) (3)	Land Aquisition Cost (at $10,000/ acre) ($) (4)	Excavation Cost for 20 ft Excavation at $0.57/cu yd ($) (5)	Lining Cost at $6.46/ sq yd ($) (6)	Engineering and Facilities Cost[3] ($) (7)	Total Initial Investment (4)+(5)+ (6)+(7) ($) (8)
0.5	0.1110	1.2810	12,810	23,560	107,875	10,000	154,248
1.0	0.2222	2.5500	25,500	46,907	175,438	10,000	257,848
2.0	0.5184	5.9509	59,509	109,449	332,243	10,000	511,201
3.0	0.8333	9.5648	95,648	175,915	484,380	10,000	765,943
4.0	0.1111	12.7520	127,520	234,533	612,692	10,000	984,745
5.0	1.3888	15.9410	159,410	293,188	737,670	10,000	1,200,269
6.0	1.6665	19.1290	191,290	351,825	860,187	10,000	1,413,304
7.0	1.9443	22.3170	223,170	410,460	980,868	10,000	1,624,503
8.0	2.2207	25.5059	255,059	469,103	1,100,108	10,000	1,834,269
9.0	2.4998	28.6937	286,937	527,734	1,218,134	10,000	2,042,806
10.0	2.7776	31.8825	318,825	586,383	1,335,203	10,000	2,250,411

[1] To derive the fill volume of these debris, divide the tonnage in col. 2 by a fill density of 0.02 ton/cu. ft.

[2] The fill volume of debris in col. 2 equals a rectangle having the acreage in col. 3 as floor and a height of 100 feet.

[3] Equally divided between engineering and facility costs.

TABLE 20 - Manpower Requirements and Cost for Recycling Plant

Description of Worker	Hourly Wage in Dollars per Man-Hour	Manpower Requirement, in Numbers of Men			
		Plant Capacity			
		120-300 TPH	300-450 TPH	450-600 TPH	600-750 TPH
Laborer	11.01	2	4	4	4
Loader Operator	12.32	1	1	1	1
Crane Operator	14.78	-	-	1	1
Bulldozer Operator	14.25	1	1	1	2
Backhoe Operator	12.32	1	2	2	2
Crusher Operator	13.50	1	1	1	2

TABLE 21 - Hourly Overhead Cost

Plant Capacity (TPH)	Production Rate (TPH)	Production Characteristics	Quantity of Processed Debris (million tons/year)						
			0.2	0.4	0.6	0.8	1.0	1.2	1
600-750	750	Hours of Opr. (hr/yr)	267	533	801	1,067	1,335	1,602	1
		Overhead Cost ($/hr)	41.10	20.59	13.70	10.28	8.22	6.85	5
	675	Hours of Opr. (hr/yr)	296	593	889	1,185	1,481	1,778	
		Overhead Cost ($/hr)	37.07	18.51	12.34	9.26	7.41	6.17	
450-600	600	Hours of Opr. (hr/yr)	333	667	1,000	1,333	1,667	2,000	
		Overhead Cost ($/hr)	27.58	13.77	9.19	6.89	5.51	4.59	
	525	Hours of Opr. (hr/yr)	381	762	1,143	1,524	1,905		
		Overhead Cost ($/hr)	24.11	12.05	8.04	6.03	4.82		
300-450	450	Hours of Opr. (hr/yr)	444	889	1,333	1,778			
		Overhead Cost ($/hr)	15.50	7.74	5.16	3.87			
	375	Hours of Opr. (hr/yr)	533	1,067	1,600				
		Overhead Cost ($/hr)	12.91	6.45	4.30				
120-300	300	Hours of Opr. (hr/yr)	667	1,333	2,000				
		Overhead Cost ($/hr)	6.71	3.36	2.24				
	225	Hours of Opr. (hr/yr)	888	1,778					
		Overhead Cost ($/hr)	5.04	2.52					
	120	Hours of Opr. (hr/yr)	1,666						
		Overhead Cost ($/hr)	2.69						

TABLE 22 - Hourly Interest and Insurance Cost

Plant Capacity (TPH)	Production Rate (TPH)	Production Characteristics	Quantity of Processed Debris (million tons/year)						
			0.2	0.4	0.6	0.8	1.0	1.2	1.4
600-750	750	Hours of Opr. (hrs/yr)	267	533	801	1,067	1,335	1,602	1,869
		Mult. Factor	0.2247	0.1124	0.0750	0.0562	0.0450	0.0375	0.0321
		Int. & Insur. ($/hr)	493.16	246.69	164.61	123.34	98.76	82.3	70.45
	675	Hours of Opr. (hrs/yr)	296	593	889	1,185	1,481	1,778	
		Mult. Factor	0.2027	0.1014	0.0675	0.0506	0.0405	0.0337	
		Int. & Insur. ($/hr)	444.88	222.55	148.15	111.05	88.89	73.96	
450-600	600	Hours of Opr. (hrs/yr)	333	667	1,000	1,333	1,667	2,000	
		Mult. Factor	0.1802	0.0901	0.0600	0.0450	0.0360	0.0300	
		Int. & Insur. ($/hr)	331.05	165.53	110.23	82.67	66.14	55.11	
	525	Hours of Opr. (hrs/yr)	381	762	1,143	1,524	1,905		
		Mult. Factor	0.1575	0.0787	0.0525	0.0394	0.0315		
		Int. & Insur.	289.35	144.86	96.45	72.38	57.87		
300-450	450	Hours of Opr. (hrs/yr)	444	889	1,333	1,778			
		Mult. Factor	0.1351	0.0676	0.0450	0.0337			
		Int. & Insur. ($/hr)	189.84	94.99	63.23	47.35			
	375	Hours of Opr. (hrs/yr)	533	1,067	1,600				
		Mult. Factor	0.1126	0.0563	0.0375				
		Int. & Insur. ($/hr)	158.22	79.11	52.69				

TABLE 21 - Hourly Overhead Cost

Plant Capacity (TPH)	Production Rate (TPH)	Production Characteristics	Quantity of Processed Debris (million tons/year)						
			0.2	0.4	0.6	0.8	1.0	1.2	1.4
600-750	750	Hours of Opr. (hr/yr)	267	533	801	1,067	1,335	1,602	1,869
		Overhead Cost ($/hr)	41.10	20.59	13.70	10.28	8.22	6.85	5.87
	675	Hours of Opr. (hr/yr)	296	593	889	1,185	1,481	1,778	
		Overhead Cost ($/hr)	37.07	18.51	12.34	9.26	7.41	6.17	
450-600	600	Hours of Opr. (hr/yr)	333	667	1,000	1,333	1,667	2,000	
		Overhead Cost ($/hr)	27.58	13.77	9.19	6.89	5.51	4.59	
	525	Hours of Opr. (hr/yr)	381	762	1,143	1,524	1,905		
		Overhead Cost ($/hr)	24.11	12.05	8.04	6.03	4.82		
300-450	450	Hours of Opr. (hr/yr)	444	889	1,333	1,778			
		Overhead Cost ($/hr)	15.50	7.74	5.16	3.87			
	375	Hours of Opr. (hr/yr)	533	1,067	1,600				
		Overhead Cost ($/hr)	12.91	6.45	4.30				
120-300	300	Hours of Opr. (hr/yr)	667	1,333	2,000				
		Overhead Cost ($/hr)	6.71	3.36	2.24				
	225	Hours of Opr. (hr/yr)	888	1,778					
		Overhead Cost ($/hr)	5.04	2.52					
	120	Hours of Opr. (hr/yr)	1,666						
		Overhead Cost ($/hr)	2.69						

TABLE 22 - Continued

120-300	300	Hours of Opr. (hrs/yr)	667	1,333	2,000
		Mult. Factor	0.0900	0.0450	0.0300
		Int. & Insur. ($/hr)	80.59	40.29	26.86
	225	Hours of Opr. (hrs/yr)	888	1,778	
		Mult. Factor	0.0630	0.0320	
		Int. & Insur. ($/hr)	56.41	28.65	
	120	Hours of Opr. (hrs/yr)	1,666		
		Mult. Factor	0.0360		
		Int. & Insur. ($/hr)	32.23		

TABLE 23 - Hourly Production Cost - (Write-off Cost + Depreciation Cost)

Plant Capacity (TPH)	Production Rate (TPH)	Production Characteristics	Quantity of Processed Debris (million tons/year)						
			0.2	0.4	0.6	0.8	1.0	1.2	1.4
600-750	750	Hours of Opr. (hr/yr)	267	533	801	1,067	1,335	1,602	1,869
		Cost ($/hr)	907.41	640.43	551.46	506.77	480.13	462.30	449.47
	657	Hours of Opr. (hr/yr)	296	593	889	1,185	1,481	1,778	
		Cost ($/hr)	855.10	614.21	533.64	493.46	469.45	453.28	
450-600	600	Hours of Opr. (hr/yr)	333	667	1,000	1,333	1,667	2,000	
		Cost ($/hr)	678.79	499.46	439.58	409.72	391.81	379.86	
	525	Hours of Opr. (hr/yr)	381	762	1,143	1,524	1,905		
		Cost ($/hr)	633.62	477.07	424.65	398.57	382.85		
300-450	450	Hours of Opr. (hr/yr)	444	889	1,333	1,778			
		Cost ($/hr)	470.59	367.98	333.64	316.47			
	375	Hours of Opr. (hr/yr)	533	1,067	1,600				
		Cost ($/hr)	436.38	350.81	322.24				
120-300	300	Hours of Opr. (hr/yr)	667	1,333	2,000				
		Cost ($/hr)	256.08	212.43	197.88				
	225	Hours of Opr. (hr/yr)	888	1,778					
		Cost ($/hr)	230.23	199.95					
	120	Hours of Opr. (hr/yr)	1,666						
		Cost ($/hr)	203.70						

TABLE 24 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 0.5 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	0.1389	0.1111	0.0833	0.0555	0.0277	0.0034
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	0.1634	0.1307	0.0998	0.0654	0.03268	0.0041
1.3 Recycling Plant #1. a. used capacity (TPH) b. operating period (hrs/year)	 300 545	 300 436	 300 332			
1.4 Recycling Plant #2 a. used capacity (TPH) b. operating period (hrs/year)						
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	0.1389	0.1111	0.0833			
1.6 Fill rate of non-concrete debris (tons/day)	800	800	800			
1.7 Fill rate of non-concrete debris (million tons/year)	0.0463	0.0370	0.0277			
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1 2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	895,410					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	29,261	23,408	17,825			

TABLE 24 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	30,020	30,020	30,020			
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	59,281	53,429	47,845			
2.5 Production cost excluding depreciation and write-off cost ($/year)	139,564	111,651	85,019			
2.6 Sale of equipment ($)			629,086			
Recycling Plant #2						
2.7 Initial investment in recycling plant (Table 18, col 4)($)						
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)						
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)						
2.10 Total depreciation cost (2.8 + 2.9)($/year)						
2.11 Production cost excluding depreciation cost ($/year)						
2.12 Sale of equipment ($)						
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	154,248					
3.2 Production cost (after Fig. 20) ($/year)	115,750	103,600	99,720			
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	18,966	15,173	11,554			

TABLE 24 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	47,158	47,158	47,158			
3.5 Property tax (7.5% on value of land and facilities)($/year)	1,338	1,338	1,338			
3.6 Sale of Land ($)			17,294			
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	231,963	185,537	139,111			
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	34,725	27,775	20,825			
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	231,500	185,000	138,500			
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	198,845	165,080	132,864			
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)						
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	183,212	167,269	159,770			
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	498,188	398,312	298,436			
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	382,052	332,349	292,634			
4.9 Operating income (lines 4.7 - 4.8)($/year)	116,136	65,963	5,802			

TABLE 24 - Continued

4.10 Income Tax (50% of the operating income)	58,068	32,982	2,901			
4.11 Net Income	58,068	32,982	2,901			
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	164,507	133,569	97,904			
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	53,219	50,293	47,501			
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	217,726	183,862	145,405			
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)			646,380			
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+217,726	+183,862	+791,785			
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-1,049,658					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+189,326	+139,026	+520,611			
5.8 Net present value ($)	-200,695					

TABLE 25 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 1.0 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	0.2778	0.2222	0.1666	0.1111	0.0555	0.0069
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	0.3268	0.2614	0.1960	0.1307	0.0654	0.0082
1.3 Recycling Plant #1.						
a. used capacity (TPH)	300	300	300			
b. operating period (hrs/year)	1,089	871	653			
1.4 Recycling Plant #2						
a. used capacity (TPH)						
b. operating period (hrs/year)						
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	0.2778	0.2222	0.1666			
1.6 Fill rate of non-concrete debris (tons/day)	680	680	680			
1.7 Fill rate of non-concrete debris (million tons/year)	0.0923	0.0741	0.0555			
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1						
2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	895,410					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	58,468	46,764	35,059			

TABLE 25 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	30,020	30,020	30,020			
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	88,488	76,784	65,079			
2.5 Production cost excluding depreciation and write-off cost ($/year)	255,104	223,046	167,220			
2.6 Sale of equipment ($)			665,059			
Recycling Plant #2						
2.7 Initial investment in recycling plant (Table 18, col 4)($)						
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)						
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)						
2.10 Total depreciation cost (2.8 + 2.9)($/year)						
2.11 Production cost excluding depreciation cost ($/year)						
2.12 Sale of equipment ($)						
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	257,848					
3.2 Production cost (after Fig. 20) ($/year)	173,524	148,200	130,425			
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	40,740	29,100	23,280			

TABLE 25 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	77,449	77,449	77,449			
3.5 Property tax (7.5% on value of land and facilities)($/year)	2,288	2,288	2,288			
3.6 Sale of Land ($)						
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	463,926	371,074	278,222			
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	69,450	55,550	41,650			
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	461,500	370,500	277,500			
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	343,592	299,830	232,299			
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)						
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	294,001	257,037	233,442			
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	994,876	797,124	597,372			
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	637,593	556,867	465,741			
4.9 Operating income (lines 4.7 - 4.8)($/year)	357,283	240,257	131,631			

TABLE 25 - Continued

4.10 Income Tax (50% of the operating income)	178,642	120,129	65,816			
4.11 Net Income	178,642	120,129	65,816			
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	344,579	274,362	208,344			
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	82,969	77,116	71,264			
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	427,548	351,479	279,608			
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)			699,484			
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+ 427,548	+ 351,479	+ 979,092			
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-1,153,258					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+ 371,780	+ 265,768	+ 643,769			
5.8 Net present value ($)	+ 128,060					

TABLE 26 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 2.0 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	0.5556	0.4444	0.3333	0.2222	0.1111	0.0138
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	0.6536	0.5228	0.3920	0.2614	0.1307	0.0163
1.3 Recycling Plant #1.						
a. used capacity (TPH)	300	300	300	300		
b. operating period (hrs/year)	2,000	1,742	1,307	871		
1.4 Recycling Plant #2						
a. used capacity (TPH)						
b. operating period (hrs/year)						
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	0.5100	0.4444	0.3333	0.2222		
1.6 Fill rate of non-concrete debris (tons/day)	680	680	680	680		
1.7 Fill rate of non-concrete debris (million tons/year)	0.1700	0.1250	0.1111	0.0741		
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1						
2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	895,410					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	107,380	93,527	73,555	46,764		

TABLE 26 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	22,515	22,515	22,515	22,515		
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	129,895	116,042	96,070	69,279		
2.5 Production cost excluding depreciation and write-off cost ($/year)	395,760	357,380	277,646	223,046		
2.6 Sale of equipment ($)				484,122		
Recycling Plant #2						
2.7 Initial investment in recycling plant (Table 18, col 4)($)						
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)						
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)						
2.10 Total depreciation cost (2.8 + 2.9)($/year)						
2.11 Production cost excluding depreciation cost ($/year)						
2.12 Sale of equipment ($)						
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	511,201					
3.2 Production cost (after Fig. 20) ($/year)	269,900	215,000	197,777	148,200		
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	69,840	58,200	46,560	29,100		

TABLE 26 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	112,923	112,923	112,923	112,923		
3.5 Property tax (7.5% on value of land and facilities)($/year)	4,838	4,838	4,838	4,838		
3.6 Sale of Land ($)				80,337		
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	851,700	742,148	556,611	371,974		
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	127,500	111,100	83,325	55,550		
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	850,000	625,000	555,500	370,500		
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	525,655	473,422	373,716	292,325		
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)						
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	457,501	390,961	362,098	295,061		
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	1,829,200	1,478,248	1,195,436	797,124		
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	983,156	864,383	735,814	587,386		
4.9 Operating income (lines 4.7 - 4.8)($/year)	846,044	613,865	459,622	209,738		

TABLE 26 - Continued

4.10 Income Tax (50% of the operating income)	423,022	306,933	229,811	104,869		
4.11 Net Income	423,022	306,933	229,811	104,869		
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	665,840	535,898	438,804	287,071		
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	121,409	114,483	104,497	91,101		
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	787,249	650,381	543,301	391,568		
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)				564,459		
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+787,249	+650,381	+543,301	+956,027		
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-1,406,611					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+684,564	+491,781	+357,229	+475,314		
5.8 Net present value ($)	+602,277					

TABLE 27 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 3.0 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	0.8334	0.6666	0.4999	0.3333	0.1666	0.0208
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	0.9805	0.7842	0.5880	0.3922	0.1961	0.0245
1.3 Recycling Plant #1.						
a. used capacity (TPH)	300	300	300	300	300	
b. operating period (hrs/year)	2,000	2,000	1,960	1,307	654	
1.4 Recycling Plant #2						
a. used capacity (TPH)						
b. operating period (hrs/year)						
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	0.5100	0.5100	0.4999	0.3333	0.1666	
1.6 Fill rate of non-concrete debris (tons/day)	680	680	680	680	680	
1.7 Fill rate of non-concrete debris (million tons/year)	0.1700	0.1700	0.1667	0.1111	0.0555	
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1						
2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	895,410					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	107,380	107,380	102,333	70,173	35,113	

TABLE 27 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	18.012	18,012	18,012	18,012	18,012	
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	125,392	125,392	120,345	88,185	53,125	
2.5 Production cost excluding depreciation and write-off cost ($/year)	395,760	395,760	387,845	277,646	167,476	
2.6 Sale of equipment ($)					382,971	
Recycling Plant #2						
2.7 Initial investment in recycling plant (Table 18, col 4)($)						
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)						
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)						
2.10 Total depreciation cost (2.8 + 2.9)($/year)						
2.11 Production cost excluding depreciation cost ($/year)						
2.12 Sale of equipment ($)						
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	765,943					
3.2 Production cost (after Fig. 20) ($/year)	263,500	263,500	263,000	197,777	130,425	
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	69,840	69,840	69,840	46,560	23,280	

TABLE 27 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	134,059	134,059	134,059	134,059	134,059	
3.5 Property tax (7.5% on value of land and facilities)($/year)	7,549	7,549	7,549	7,549	7,549	
3.6 Sale of Land ($)					129,124	
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	851,700	851,700	835,000	556,661	278,222	
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	127,500	127,500	125,000	83,333	41,650	
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	850,000	850,000	833,500	555,500	277,500	
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	521,152	521,152	508,190	365,831	220,601	
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)						
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	474,948	474,948	474,948	385,945	295,313	
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	1,829,200	1,829,200	1,793,500	1,195,494	597,372	
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	996,100	996,100	983,138	751,776	515,914	
4.9 Operating income (lines 4.7 - 4.8)($/year)	833,100	833,100	810,362	443,718	81,458	

TABLE 27 - Continued

4.10 Income Tax (50% of the operating income)	416,550	416,550	405,181	221,859	40,729	
4.11 Net Income	416,550	416,550	405,181	221,859	40,729	
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	676,001	676,001	659,585	444,103	227,913	
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	129,726	129,726	127,202	111,122	93,592	
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	805,727	805,727	786,787	555,225	321,505	
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)						
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+ 805,727	+805,727	+786,787	+555,225	+833,600	
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-1,661,353					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+700,632	+609,245	+517,325	+317,452	+414,446	
5.8 Net present value ($)	+897,747					

TABLE 28 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 4.0 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	1.1111	0.8888	0.6666	0.4444	0.2222	0.02778
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	1.3073	1.0456	0.784	0.5229	0.2614	0.0327
1.3 Recycling Plant #1.						
a. used capacity (TPH)	300	300	300	300	300	
b. operating period (hrs/year)	2,000	2,000	2,000	1,743	871	
1.4 Recycling Plant #2						
a. used capacity (TPH)	300	300	300			
b. operating period (hrs/year)	2,000	1,485	613			
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	1.02	0.8888	0.6666	0.4444	0.2222	
1.6 Fill rate of non-concrete debris (tons/day)	1,360	1360/680*	1360/680*	680	680	
1.7 Fill rate of non-concrete debris (million tons/year)	0.34	0.2963	0.2222	0.1481	0.0741	
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1						
2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	895,410					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	107,380	107,380	107,380	93,582	46,764	

*both plants are in operation/only one plant is in operation

TABLE 28 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	18,012	18,012	18,012	18,012	18,012	
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	125,392	125,392	125,392	111,594	64,776	
2.5 Production cost excluding depreciation and write-off cost ($/year)	395,760	395,760	395,760	357,585	223,045	
2.6 Sale of equipment ($)					342,864	
Recycling Plant #2						
2.7 Initial investment in recycling plant (Table 18, col 4)($)	895,410					
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)	107,380	79,730	32,912			
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)	30,020	30,020	20,020			
2.10 Total depreciation cost (2.8 + 2.9)($/year)	137,400	109,750	62,932			
2.11 Production cost excluding depreciation cost ($/year)	395,760	315,459	156,977			
2.12 Sale of equipment ($)			585,328			
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	984,745					
3.2 Production cost (after Fig. 20) ($/year)	442,000	385,190	266,600	236,960	148,200	
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	139,680	122,220	93,120	58,200	29,100	

TABLE 28 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	171,445	171,445	141,445	171,445	171,445	
3.5 Property tax (7.5% on value of land and facilities)($/year)	9,939	9,939	9,939	9,939	9,939	
3.6 Sale of Land ($)					172,152	
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	1,703,400	1,484,296	1,113,222	742,148	371,107	
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	255,000	222,200	166,650	111,100	55,555	
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	1,700,000	1,481,500	1,111,000	740,500	370,500	
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	521,152	521,152	521,152	469,179	287,821	
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)	533,160	425,209	219,909		—	
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	763,064	688,794	541,104	476,544	358,684	
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	3,658,400	3,187,996	2,390,872	1,593,748	797,162	
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	1,817,376	1,635,155	1,282,165	945,723	646,505	
4.9 Operating income (lines 4.7 - 4.8)($/year)	1,841,024	1,552,841	1,108,707	648,025	150,657	

TABLE 28 - Continued

4.10 Income Tax (50% of the operating income)	920,512	776,420	554,354	324,013	75,329	
4.11 Net Income	920,512	776,420	554,354	324,013	75,329	
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	1,354,749	1,183,008	914,123	607,052	193,439	
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	217,119	203,293	179,884	141,520	118,111	
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	1,571,867	1,386,301	1,094,007	748,571	311,550	
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)			585,328		515,016	
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+1,571,867	+1,386,301	+1,679,335	+ 748,571	+ 826,506	
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-2,775,565					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+1,366,841	+1,048,243	+1,104,190	+427,998	+410,949	
5.8 Net present value ($)	+1,582,656					

TABLE 29 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 5.0 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	1.3888	1.1111	0.8333	0.5555	0.2777	0.835
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	1.6341	1.3071	0.9800	0.6536	0.3268	0.0408
1.3 Recycling Plant #1.						
a. used capacity (TPH)	450	450	450	450	375	
b. operating period (hrs/year)	2,000	2,000	2,000	1,452	871	
1.4 Recycling Plant #2						
a. used capacity (TPH)	300	300				
b. operating period (hrs/year)	2,000	1,357				
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	1.275	1.1111	0.765	0.5555	0.2777	
1.6 Fill rate of non-concrete debris (tons/day)	1,700	1700/1020*	1,020	1,020	1,020	
1.7 Fill rate of non-concrete debris (million tons/year)	0.425	0.3704	0.255	0.1852	0.0926	
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1						
2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	1,376,095					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	164,740	164,740	164,740	119,601	71,744	

*both plants are in operation/only one plant is in operation.

TABLE 29 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	28,119	28,119	28,119	28,119	28,119	
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	192,859	192,859	192,859	147,720	99,863	
2.5 Production cost excluding depreciation and write-off cost ($/year)	632,940	632,940	632,940	484,495	342,821	
2.6 Sale of equipment ($)					549,934	
Recycling Plant #2						
2.7 Initial investment in recycling plant (Table 18, col 4)($)	895,410					
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)	107,380	72,857				
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)	45,030	45,030				
2.10 Total depreciation cost (2.8 + 2.9)($/year)	152,410	117,887				
2.11 Production cost excluding depreciation cost ($/year)	395,760	288,267				
2.12 Sale of equipment ($)		625,113				
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	1,200,269					
3.2 Production cost (after Fig. 20) ($/year)	510,000	451,900	344,250	277,800	175,940	
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	174,600	151,320	104,760	78,570	43,650	

TABLE 29 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	208,172	208,172	208,172	208,172	208,172	
3.5 Property tax (7.5% on value of land and facilities)($/year)	12,330	12,330	12,330	12,330	12,330	
3.6 Sale of Land ($)					215,203	
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	2,129,250	1,855,537	1,277,550	927,685	463,759	
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	318,750	277,775	191,250	138,875	69,425	
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	2,125,000	1,852,000	1,275,000	926,000	463,000	
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	825,799	825,799	825,799	632,165	442,684	
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)	548,170	406,154				
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	905,102	823,722	699,512	576,872	440,092	
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	4,573,000	3,985,312	2,743,800	1,992,560	996,184	
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	2,279,071	2,055,675	1,495,311	1,209,037	882,776	
4.9 Operating income (lines 4.7 - 4.8)($/year)	2,293,929	1,929,637	1,248,489	783,523	113,408	

TABLE 29 - Continued

4.10 Income Tax (50% of the operating income)	1,146,965	964,819	624,245	391,762	56,704	
4.11 Net Income	1,146,965	964,819	624,245	391,762	56,704	
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	1,700,406	1,483,737	1,025,276	747,654	364,739	
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	276,721	259,459	200,516	177,946	154,018	
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	1,977,126	1,743,196	1,225,791	747,654	518,757	
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)		625,113			765,137	
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+1,977,126	+2,368,309	+1,225,791	+747,654	+1,283,894	
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-3,471,774					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+1,719,240	+1,790,781	+805,977	+427,473	+638,322	
5.8 Net present value ($)	+1,910,020					

TABLE 30 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 6.0 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	1.6667	1.3333	1.0000	0.6667	0.3333	0.0416
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	1.9609	1.5685	1.1760	0.7843	0.3922	0.0490
1.3 Recycling Plant #1. a. used capacity (TPH) b. operating period (hrs/year)	 450 2,000	 450 2,000	 450 2,000	 450 1,742	 450 872	
1.4 Recycling Plant #2 a. used capacity (TPH) b. operating period (hrs/year)	 450 2,000	 450 1,485	 450 613			
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	1.53	1.3333	1.0000	0.6667	0.3333	
1.6 Fill rate of non-concrete debris (tons/day)	2,040	2040/1020*	2040/1020*	1,020	1,020	
1.7 Fill rate of non-concrete debris (million tons/year)	0.51	0.4444	0.3333	0.2222	0.1111	
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1 2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	1,376,095					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	164,740	164,740	164,740	143,488	71,826	

*both plants are in operation/only one plant is in operation.

TABLE 30 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	28,119	28,119	28,119	28,119	28,119	
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	192,859	192,859	192,859	171,607	99,945	
2.5 Production cost excluding depreciation and write-off cost ($/year)	632,940	632,940	632,940	551,291	320,878	
2.6 Sale of equipment ($)					525,965	
Recycling Plant #2						
2.7 Initial investment in recycling plant (Table 18, col 4)($)	1,376,095					
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)	164,740	122,319	50,493			
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)	46,865	46,865	46,865			
2.10 Total depreciation cost (2.8 + 2.9)($/year)	111,605	169,184	97,358			
2.11 Production cost excluding depreciation cost ($/year)	632,940	478,526	267,500			
2.12 Sale of equipment ($)			897,948			
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	1,413,304					
3.2 Production cost (after Fig. 20) ($/year)	601,800	533,330	426,667	311,111	192,222	
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	209,520	183,330	139,680	87,300	43,650	

TABLE 30 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	244,403	244,403	244,403	244,403	244,403	
3.5 Property tax (7.5% on value of land and facilities)($/year)	14,722	14,722	14,722	14,722	14,722	
3.6 Sale of Land ($)					258,242	
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	2,555,100	2,226,611	1,670,000	1,113,389	556,611	
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	382,500	333,325	250,000	166,675	83,325	
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	2,550,000	2,222,000	1,666,500	1,111,000	555,500	
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	825,799	825,799	825,799	722,898	420,823	
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)	744,545	647,710	364,858			
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	1,070,445	975,785	825,472	657,536	494,997	
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	5,487,600	4,781,936	3,586,500	2,391,064	1,195,436	
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	2,640,789	2,449,294	2,016,129	1,380,434	915,820	
4.9 Operating income (lines 4.7 - 4.8)($/year)	2,846,811	2,332,642	1,570,371	1,010,630	279,616	

TABLE 30 - Continued

4.10 Income Tax (50% of the operating income)	1,423,406	1,166,321	785,186	505,315	139,808	
4.11 Net Income	1,423,406	1,116,321	785,186	505,315	139,808	
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	1,972,273	1,772,767	1,319,806	921,325	484,156	
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	274,434	303,223	267,310	208,005	172,174	
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	2,246,706	2,075,990	1,587,116	1,129,330	656,330	
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)			897,948		784,207	
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+2,246,706	+2,075,990	+2,485,064	+1,129,330	+1,440,537	
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-4,165,494					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+1,953,657	+1,569,747	+1,633,970	+645,698	+716,201	
5.8 Net present value ($)	+2,353,799					

TABLE 31 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 7.0 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	1.9444	1.5556	1.1662	0.7778	0.3889	0.0486
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	2.2878	1.8299	1.3720	0.9150	0.4575	0.0572
1.3 Recycling Plant #1.						
a. used capacity (TPH)	600	600	600	600	600	
b. operating period (hrs/year)	2,000	2,000	2,000	1,525	763	
1.4 Recycling Plant #2						
a. used capacity (TPH)	450	450				
b. operating period (hrs/year)	2,000	1,400				
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	1.785	1.556	1.02	0.7778	0.3889	
1.6 Fill rate of non-concrete debris (tons/day)	2,380	2380/1360*	1,360	1,360	1,360	
1.7 Fill rate of non-concrete debris (million tons/year)	0.595	0.5185	0.34	0.25923	0.1296	
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1						
2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	1,837,150					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	221,500	221,500	221,500	168,894	84,502	

*both plants are in operation/only one plant is in operation.

TABLE 31 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	35,190	35,190	35,190	35,190	35,190	
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	256,690	256,690	256,690	204,084	119,692	
2.5 Production cost excluding depreciation and write-off cost ($/year)	759,720	759,720	759,720	597,510	381,088	
2.6 Sale of equipment ($)					743,304	
Recycling Plant #2 2.7 Initial investment in recycling plant (Table 18, col 4)($)	1,376,095					
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)	164,740	115,318				
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)	70,298	70,298				
2.10 Total depreciation cost (2.8 + 2.9)($/year)	235,038	185,616				
2.11 Production cost excluding depreciation cost ($/year)	632,940	467,096				
2.12 Sale of equipment ($)		955,442				
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	1,624,503					
3.2 Production cost (after Fig. 20) ($/year)	654,000	611,830	408,000	347,060	220,350	
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	244,440	209,520	139,680	104,760	58,200	

TABLE 31 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	280,267	280,267	280,267	280,267	280,267	
3.5 Property tax (7.5% on value of land and facilities)($/year)	17,113	17,113	17,113	17,113	17,113	
3.6 Sale of Land ($)					301,280	
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	2,980,950	2,597,785	1,703,400	1,298,926	649,463	
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	446,250	388,890	255,000	194,450	97,225	
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	2,975,000	2,592,500	1,700,000	1,296,150	648,000	
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	1,016,410	1,016,410	1,016,410	801,594	500,780	
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)	867,978	652,712				
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	1,195,820	1,118,730	845,060	749,200	575,930	
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	6,402,200	5,579,175	3,658,400	2,789,526	1,394,688	
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	3,080,208	2,787,852	1,861,470	1,550,794	1,076,710	
4.9 Operating income (lines 4.7 - 4.8)($/year)	3,321,992	2,791,323	1,796,930	1,238,732	317,978	

TABLE 31 - Continued

4.10 Income Tax (50% of the operating income)	1,660,996	1,395,662	898,465	619,366	158,989	
4.11 Net Income	1,660,996	1,395,662	898,465	619,366	158,989	
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	2,432,991	2,118,234	1,435,423	1,103,717	558,948	
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	385,998	361,286	268,479	242,176	199,980	
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	2,818,989	2,479,520	1,703,902	1,345,892	758,928	
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)		955,442			1,044,584	
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+2,818,989	+3,434,962	+1,703,902	+1,345,892	+1,803,512	
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-4,837,748					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+2,451,294	+2,597,325	+1,120,343	+769,518	+896,664	
5.8 Net present value ($)	+2,997,397					

TABLE 32 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 8.0 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	2.2222	1.7778	1.3222	0.8889	0.4444	0.0556
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	2.6146	2.0913	1.5680	1.0458	0.5229	0.0654
1.3 Recycling Plant #1. a. used capacity (TPH) b. operating period (hrs/year)	 750 2,000	 750 2,000	 750 2,000	 750 1,394	 750 697	
1.4 Recycling Plant #2 a. used capacity (TPH) b. operating period (hrs/year)	 450 2,000	 450 1,314				
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	2.04	1.7778	1.275	0.8889	0.4444	
1.6 Fill rate of non-concrete debris (tons/day)	2,720	2720/1700*	1,700	1,700	1,700	
1.7 Fill rate of non-concrete debris (million tons/year)	0.68	0.5926	0.425	0.2963	0.1481	
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1 2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	2,194,750					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	263,860	263,860	263,860	183,910	91,955	

*both plants are in operation/only one plant is in operation.

TABLE 32 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	43,170	43,170	43,170	43,170	43,170	
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	307,030	307,030	307,030	227,080	135,125	
2.5 Production cost excluding depreciation and write-off cost ($/year)	900,000	900,000	900,000	669,301	384,368	
2.6 Sale of equipment ($)					911,455	
Recycling Plant #2						
2.7 Initial investment in recycling plant (Table 18, col 4)($)	1,376,095					
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)	164,740	108,234				
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)	70,298	70,298				
2.10 Total depreciation cost (2.8 + 2.9)($/year)	235,038	178,532				
2.11 Production cost excluding depreciation cost ($/year)	632,940	438,403				
2.12 Sale of equipment ($)		962,526				
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	1,834,269					
3.2 Production cost (after Fig. 20) ($/year)	754,800	685,630	510,000	379,264	236,960	
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	279,360	244,440	174,600	116,400	58,200	

TABLE 32 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	315,842	315,842	315,842	315,842	315,842	
3.5 Property tax (7.5% on value of land and facilities)($/year)	19,504	19,504	19,504	19,504	19,504	
3.6 Sale of Land ($)					344,330	
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	3,406,800	2,968,926	2,129,250	1,670,000	742,148	
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	510,000	444,450	318,750	222,222	111,110	
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	3,400,000	2,963,000	2,125,000	1,481,500	740,500	
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	1,207,030	1,207,030	1,207,030	896,381	519,493	
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)	867,978	616,935				
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	1,369,506	1,265,416	1,019,946	831,010	630,506	
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	7,316,800	6,376,376	4,573,000	3,373,722	1,593,748	
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	3,444,514	3,089,381	2,226,976	1,727,391	1,149,999	
4.9 Operating income (lines 4.7 - 4.8)($/year)	3,872,286	3,286,995	2,346,024	1,646,331	443,749	

TABLE 32 - Continued

4.10 Income Tax (50% of the operating income)	1,936,143	1,643,498	1,173,012	823,166	221,875	
4.11 Net Income	1,936,143	1,643,498	1,173,012	823,166	221,875	
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	2,794,053	2,444,902	1,795,884	1,366,088	672,842	
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	428,955	400,702	311,436	271,461	225,484	
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	3,223,008	2,845,604	2,107,320	1,637,549	898,326	
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)		962,526			1,255,785	
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+3,223,008	+3,808,130	+2,107,320	+1,637,549	+2,154,111	
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-5,405,114					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+2,802,616	+2,879,493	+1,385,597	+936,274	+1,070,974	
5.8 Net present value ($)	+3,669,839					

TABLE 33 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 9.0 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	2.5000	2.0000	1.5000	1.0000	0.5000	0.0625
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	2.9414	2.3527	1.764	1.1765	0.5882	0.0735
1.3 Recycling Plant #1.						
a. used capacity (TPH)	750	750	750	750	750	
b. operating period (hrs/year)	2,000	2,000	2,000	1,569	784	
1.4 Recycling Plant #2						
a. used capacity (TPH)	600	600				
b. operating period (hrs/year)	2,000	1,421				
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	2.295	2.0000	1.275	1.0000	0.5000	
1.6 Fill rate of non-concrete debris (tons/day)	3,060	3060/1700*	1,700	1,700	1,700	
1.7 Fill rate of non-concrete debris (million tons/year)	0.765	0.6667	0.425	0.3333	0.1667	
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1						
2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	2,194,750					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	263,860	263,860	263,860	210,560	103,433	

*both plants are in operation/only one plant is in operation.

TABLE 33 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	43,170	43,170	43,170	43,170	43,170	
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	307,030	307,030	307,030	253,730	146,603	
2.5 Production cost excluding depreciation and write-off cost ($/year)	900,000	900,000	900,000	737,831	432,345	
2.6 Sale of equipment ($)					873,327	
Recycling Plant #2						
2.7 Initial investment in recycling plant (Table 18, col 4)($)	1,837,150					
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)	221,500	157,376				
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)	87,975	87,975				
2.10 Total depreciation cost (2.8 + 2.9)($/year)	309,475	245,351				
2.11 Production cost excluding depreciation cost ($/year)	759,720	582,212				
2.12 Sale of equipment ($)		1,282,324				
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	2,042,806					
3.2 Production cost (after Fig. 20) ($/year)	789,300	733,300	467,500	413,300	250,000	
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	314,280	279,360	174,600	130,950	72,750	

TABLE 33 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	351,174	351,174	351,174	351,174	351,174	
3.5 Property tax (7.5% on value of land and facilities)($/year)	21,895	21,895	21,895	21,895	21,895	
3.6 Sale of Land ($)					387,365	
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	3,832,650	3,340,000	2,129,250	1,670,000	835,000	
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	573,750	500,000	318,750	250,000	125,000	
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	3,825,000	3,333,500	2,125,000	1,666,500	833,500	
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	1,207,030	1,207,030	1,207,030	991,561	578,957	
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)	1,069,195	827,563				
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	1,467,649	1,385,729	1,015,169	917,319	695,819	
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	8,231,400	7,173,500	4,573,000	3,586,500	1,793,500	
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	3,743,874	3,420,322	2,222,199	1,908,880	1,274,776	
4.9 Operating income (lines 4.7 - 4.8)($/year)	4,487,526	3,753,178	2,350,801	1,677,620	518,724	

TABLE 33 - Continued

4.10 Income Tax (50% of the operating income)	2,243,763	1,876,589	1,175,401	838,810	259,362	
4.11 Net Income	2,243,763	1,876,589	1,175,401	838,810	259,362	
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	3,211,442	2,780,144	1,833,605	1,443,714	757,139	
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	483,839	451,778	329,102	302,452	248,889	
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	3,695,282	3,231,922	2,162,707	1,746,166	1,006,028	
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)		1,282,324			1,260,692	
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+3,695,282	+4,514,246	+2,162,707	+1,746,166	+2,266,719	
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-6,074,706					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+3,213,288	+3,413,418	+1,422,015	+998,376	+1,126,960	
5.8 Net present value ($)	+4,099,352					

TABLE 34 - Economics - Net Present Value Analysis of Debris Recycling.
Total Quantity of Concrete Debris Produced: 10.0 million tons.

	Time, in years, after the start of plant operations.					
	1	2	3	4	5	6
PART I. Debris Inflow-Outflow						
1.1 Processable quantities of concrete debris each year (after Table 11) (million tons)	2.7778	2.2222	1.6666	1.1111	0.5555	0.0694
1.2 Total amount of demolition debris in the recycling system (85% concrete plus 15% non-concrete debris. See Fig. 9) (million tons)	3.2682	2.6141	1.9600	1.3071	0.6539	0.0817
1.3 Recycling Plant #1.						
a. used capacity (TPH)	750	750	750	750	750	
b. operating period (hrs/year)	2,000	2,000	2,000	1,743	872	
1.4 Recycling Plant #2						
a. used capacity (TPH)	750	750	750			
b. operating period (hrs/year)	2,000	1,466	613			
1.5 Produced quantity of recycled concrete aggregate (million tons/year)	2.55	2.2222	1.6667	1.1111	0.5556	
1.6 Fill rate of non-concrete debris (tons/day)	3,400	3400/1700*	3400/1700*	1,700	1,700	
1.7 Fill rate of non-concrete debris (million tons/year)	0.85	0.7407	0.5555	0.3704	0.1852	
PART II. Associated Costs of Recycling Plant						
Recycling Plant #1 2.1 Initial investment in recycling plant (Table 18, col. 4) ($)	2,194,750					
2.2 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.3b) ($/year)	263,860	263,860	263,860	229,954	115,043	

*both plants are in operation/only one plant is in operation.

TABLE 34 - Continued

2.3 Write-off of set-up cost (Table 18, col 3 over years of operation) ($/year)	43,170	43,170	43,170	43,170	43,170	
2.4 Sum of depreciation and write-off costs (2.2 + 2.3) ($/year)	307,030	307,030	307,030	273,124	158,213	
2.5 Production cost excluding depreciation and write-off cost ($/year)	900,000	900,000	900,000	794,608	480,873	
2.6 Sale of equipment ($)					842,323	
Recycling Plant #2 2.7 Initial investment in recycling plant (Table 18, col 4)($)	2,194,750					
2.8 Depreciation cost of purchased equipment (Table 18, col 5 x line 1.4b)($/year)	263,860	190,771	80,873			
2.9 Write-off of set-up cost (Table 18, col 3 over years of operation)($/year)	71,950	71,950	71,950			
2.10 Total depreciation cost (2.8 + 2.9)($/year)	235,810	262,721	158,823			
2.11 Production cost excluding depreciation cost ($/year)	900,000	681,377	392,584			
2.12 Sale of equipment ($)			1,443,396			
PART III. Associated Costs of SLF						
3.1 Initial investment in SLF (Table 19, col 8)	2,250,411					
3.2 Production cost (after Fig. 20) ($/year)	850,000	770,300	633,300	460,000	277,800	
3.3 Rental cost of scrapers (1 scraper for each 400 tons/day of operation at $2910/month)($/year)	349,200	305,550	232,800	160,050	72,750	

TABLE 34 - Continued

3.4 Depreciation cost (straight line depreciation over the investment period at the SLF)($/year)	386,317	386,317	386,317	386,317	386,317	
3.5 Property tax (7.5% on value of land and facilities)($/year)	24,287	24,287	24,287	24,287	24,287	
3.6 Sale of Land ($)					430,414	
PART IV Annual Income Statement						
4.1 Revenue from sale of recycled aggregate (tonnage from line 1.5, sold at $1.67/ton)($/year)	4,258,500	3,711,074	2,783,389	1,855,537	927,852	
4.2 Revenue from sale of re-bars ($0.25 per ton of concrete debris processed)($/year)	637,500	555,550	416,675	277,775	138,900	
4.3 Revenue from dumping charges ($5.00/ton of non-concrete debris)($/year)	4,250,000	3,703,500	2,777,500	1,852,000	926,000	
4.4 Production cost of recycling plant #1 (lines 2.4 + 2.5 ($/year)	1,207,030	1,207,030	1,207,030	1,067,732	639,086	
4.5 Production cost of recycling plant #2 (lines 2.10 + 2.11) ($/year)	1,135,810	944,098	551,407			
4.6 SLF operating cost (sum of lines 3.2 to 3.5)($/year)	1,609,804	1,486,454	1,276,704	1,030,654	761,154	
4.7 Operating revenues (sum of lines 4.1 to 4.3)($/year)	9,146,000	7,970,124	5,977,564	3,985,312	1,992,752	
4.8 Operating expenses (sum of lines 4.4 to 4.6)($/year)	3,952,644	3,637,582	3,035,141	2,098,386	1,400,240	
4.9 Operating income (lines 4.7 - 4.8)($/year)	5,193,356	4,332,542	2,942,423	1,886,926	592,512	

TABLE 34 - Continued

4.10 Income Tax (50% of the operating income)	2,596,678	2,166,271	1,471,212	943,463	296,256	
4.11 Net Income	2,596,678	2,166,271	1,471,212	943,463	296,256	
PART V. Cash Flow and Net Present Value Analysis						
5.1 Cash Inflow from operations without cash shield (lines 4.11 + 2.4 + 3.4)($/year)	3,525,835	3,122,339	2,323,382	1,602,904	840,786	
5.2 Tax shield (lines 2.4 + 3.4 over 2)($/year)	464,579	478,034	426,085	329,720	272,265	
5.3 Cash inflow from operations with tax shield (lines 5.1 + 5.2)($/year)	3,990,414	3,600,373	2,749,467	1,932,625	1,113,051	
5.4 Cash inflow from sale of land or equipment (lines 2.6 + 3.6) ($/year)			1,443,396		1,272,737	
5.5 Total cash inflow at the end of the year (lines 5.3 + 5.4) ($/year)	+3,990,414	+3,600,373	+4,192,863	+1,932,625	+2,385,788	
5.6 Total cash outflow for capital investment at beginning of year (lines 2.1 + 3.1)	-6,639,911					
5.7 Discounted cash inflow (15% discounted rate)($/year)	+3,469,925	+2,722,399	+2,756,875	+1,104,484	+1,186,158	
5.8 Net present value ($)	+4,600,431					

TABLE 35 - Net Present Value and Internal Rate of Return for Recycling Systems

Quantity of Concrete Debris Produced by Natural Disaster (million tons)	Plant(s) in Recycling System	Net Present Value (discount rate: 15%)	Internal Rate of Return percent
0.5	one 120-300 TPH plant operating 3 years	- 200,695	<0
1.0	one 120-300 TPH plant operating 3 years	+ 128,060	19
2.0	one 120-300 TPH plant operating 4 years	+ 602,277	32
3.0	one 120-300 TPH plant operating 5 years	+ 897,742	38
4.0	one 120-300 TPH plant operating 5 years and an additional 120-300 TPH plant operating 3 years	+1,582,656	38
5.0	one 300-450 TPH plant operating 5 years and an additional 120-300 TPH plant operating 2 years	+1,910,020	45
6.0	one 300-450 TPH plant operating 5 years and an additional 300-450 TPH plant operating 3 years	+1,953,653	45
7.0	one 450-600 TPH plant operating 5 years and a 300-450 TPH plant operating 2 years	+2,451,294	47
8.0	one 600-750 TPH plant operating 5 years and a 300-450 TPH plant operating 2 years	+3,669,839	47
9.0	one 600-750 TPH plant operating 5 years and a 450-600 TPH plant operating 2 years	+4,099,352	47
10.0	one 600-750 TPH plant operating 5 years and an additional 600-750 TPH plant operating 3 years	+4,600,431	47

TABLE 36 - Composition and Costs of Natural Aggregate Concrete and Recycled Aggregate Concrete of Equivalent Performance.

Type of Material	Natural Aggregate Concrete		Recycled Aggregate Concrete	
	Material Quantities for 1 cu yd concrete (lbs)	Material Costs ($/2000 lbs)	Material Quantities for 1 cu yd concrete (lbs)	Material Costs ($/2000 lbs)
Cement	615	50	677	50
Fine Aggregate	1230	4.0	1230	4.0
Coarse Aggregate	1845	3.3	1845	1.67

Cost of 1 cu. yd. of natural aggregate concrete:

$$615 \times \frac{50}{2000} + \frac{1230 \times 4.0}{2000} + \frac{1845 \times 3.3}{2000} = \$20.8/\text{cu. yd.}$$

Cost of 1 cu. yd. of recycled aggregate concrete:

$$677 \times \frac{50}{2000} + \frac{1230 \times 4.0}{2000} + \frac{1845 \times 1.67}{2000} = \$20.9/\text{cu. yd.}$$

TABLE 35 - Net Present Value and Internal Rate of Return for Recycling Systems

Quantity of Concrete Debris Produced by Natural Disaster (million tons)	Plant(s) in Recycling System	Net Present Value (discount rate: 15%)	Internal Rate of Return percent
0.5	one 120-300 TPH plant operating 3 years	- 200,695	<0
1.0	one 120-300 TPH plant operating 3 years	+ 128,060	19
2.0	one 120-300 TPH plant operating 4 years	+ 602,277	32
3.0	one 120-300 TPH plant operating 5 years	+ 897,742	38
4.0	one 120-300 TPH plant operating 5 years and an additional 120-300 TPH plant operating 3 years	+1,582,656	38
5.0	one 300-450 TPH plant operating 5 years and an additional 120-300 TPH plant operating 2 years	+1,910,020	45
6.0	one 300-450 TPH plant operating 5 years and an additional 300-450 TPH plant operating 3 years	+1,953,653	45
7.0	one 450-600 TPH plant operating 5 years and a 300-450 TPH plant operating 2 years	+2,451,294	47
8.0	one 600-750 TPH plant operating 5 years and a 300-450 TPH plant operating 2 years	+3,669,839	47
9.0	one 600-750 TPH plant operating 5 years and a 450-600 TPH plant operating 2 years	+4,099,352	47
10.0	one 600-750 TPH plant operating 5 years and an additional 600-750 TPH plant operating 3	+4,600,431	47

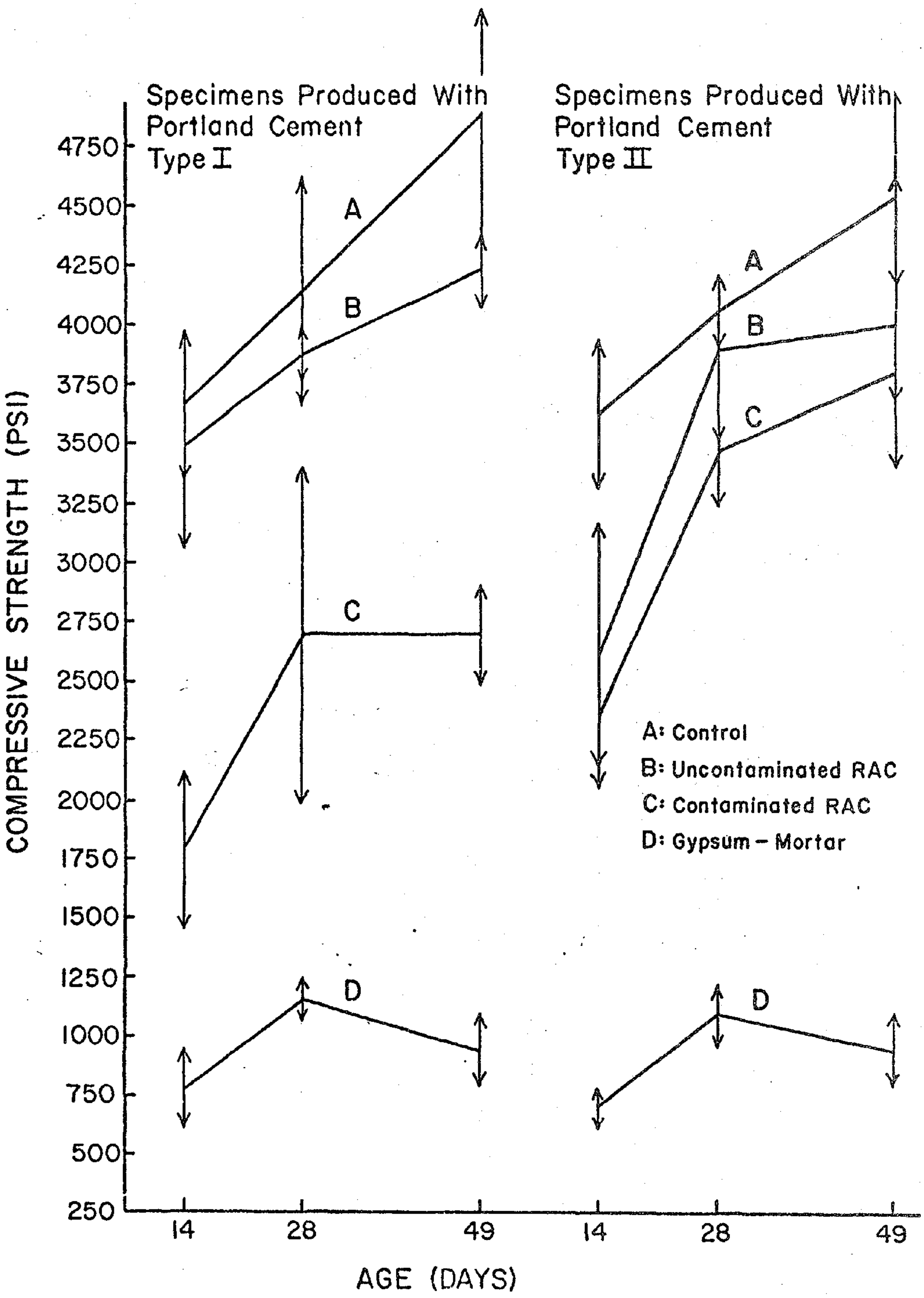

Fig. 1. - Relationship between Age and Compressive Strength. Water to Cement Ratio is 0.55.

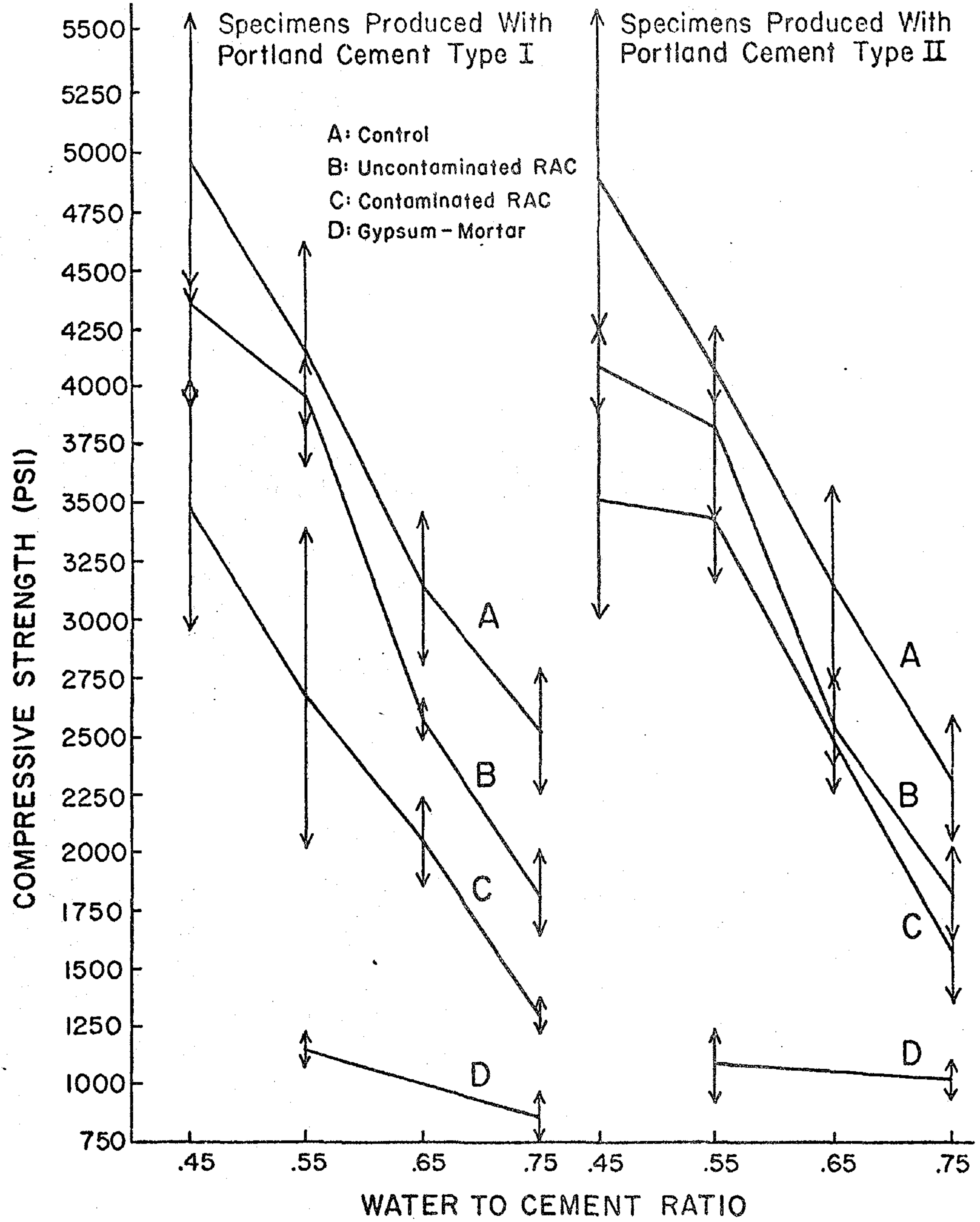

Fig. 2. - Relationship between Water to Cement Ratio and 28-Day Compressive Strength.

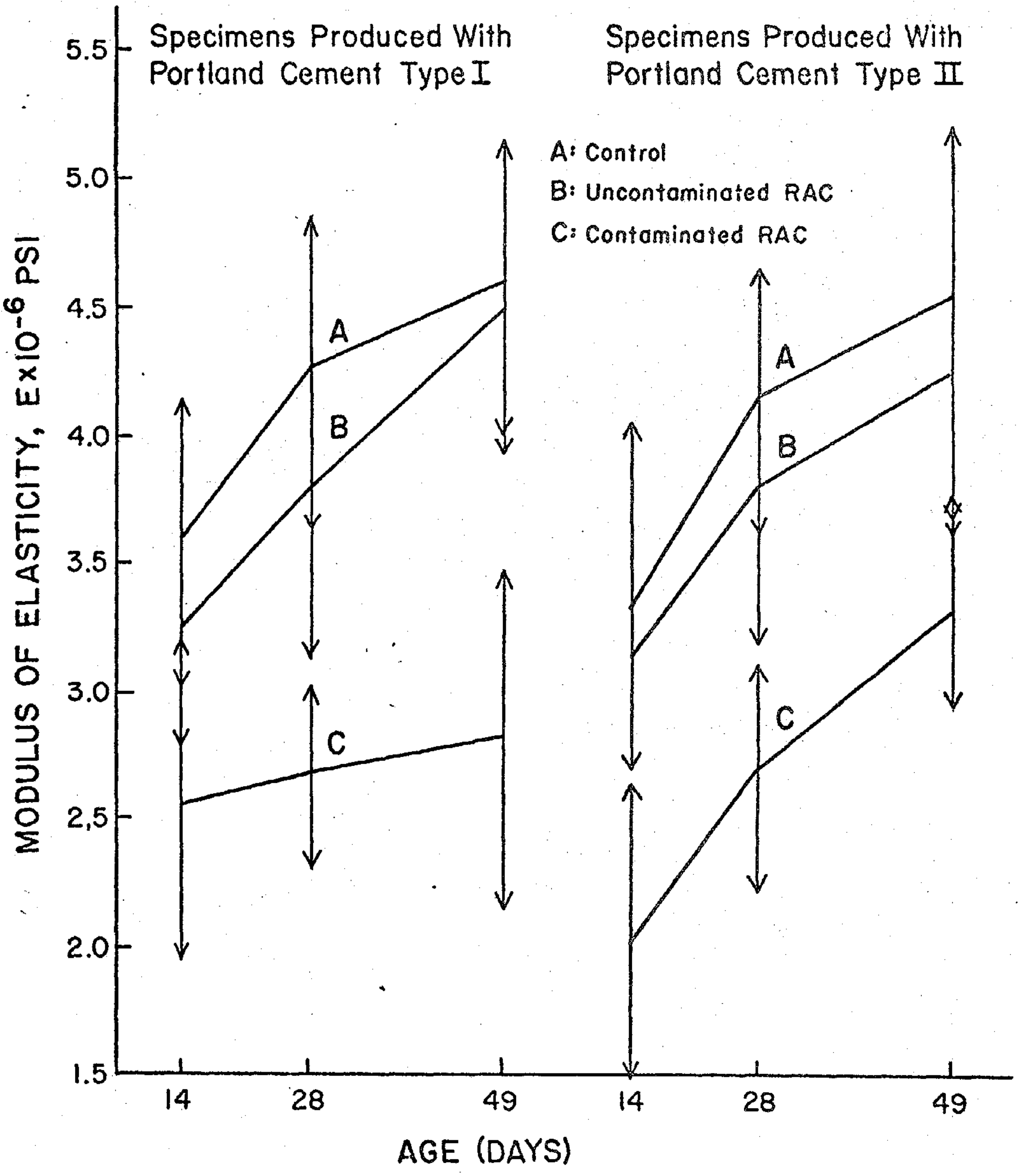

Fig. 3. - Modulus of Elasticity in Compression as a Function of Age. Water to Cement Ratio is 0.55.

Total Building Inventory in Each of the Areas Which Suffered Earthquake Intensities VII or Higher (sq. feet)			
Earthquake Intensity			
VII	VIII	IX	X
I_{VII}	I_{VIII}	I_{IX}	I_X

X

Damage Probability Matrix (after Table 1)				
Damage State	Percent of Total Square Footage Joining Each Damage State			
	Earthquake Intensity			
	VII	VIII	IX	X
Heavy	$P_{H,VII}$	$P_{H,VIII}$	$P_{H,IX}$	$P_{H,X}$
Total	$P_{T,VII}$	$P_{T,VIII}$	$P_{T,IX}$	$P_{T,X}$

=

Square Footage in Each Damage State in Each Area					Total Square Footage in Each Damage State	Amount of Concrete Debris Generated (tons/sq.ft.)	Total Amount of Concrete Debris Generated (tons)
Damage State	Earthquake Intensity						
	VII	VIII	IX	X			
Heavy	$SF_{H,VII}$	$SF_{H,VIII}$	$SF_{H,IX}$	$SF_{H,X}$	$\sum_{i=VII}^{X} SF_{H,i} = SF_H$	0.0066	$SF_H \times 0.0066$
Total	$SF_{T,VII}$	$SF_{T,VIII}$	$SF_{T,IX}$	$SF_{T,X}$	$\sum_{i=VII}^{X} SF_{T,i} = SF_T$	0.06	$SF_T \times 0.06$

TOTAL: $SF_H \times 0.0066 + SF_T \times 0.06$

FIG. 4. - Methodology for Estimating Concrete Debris Generated from Buildings.

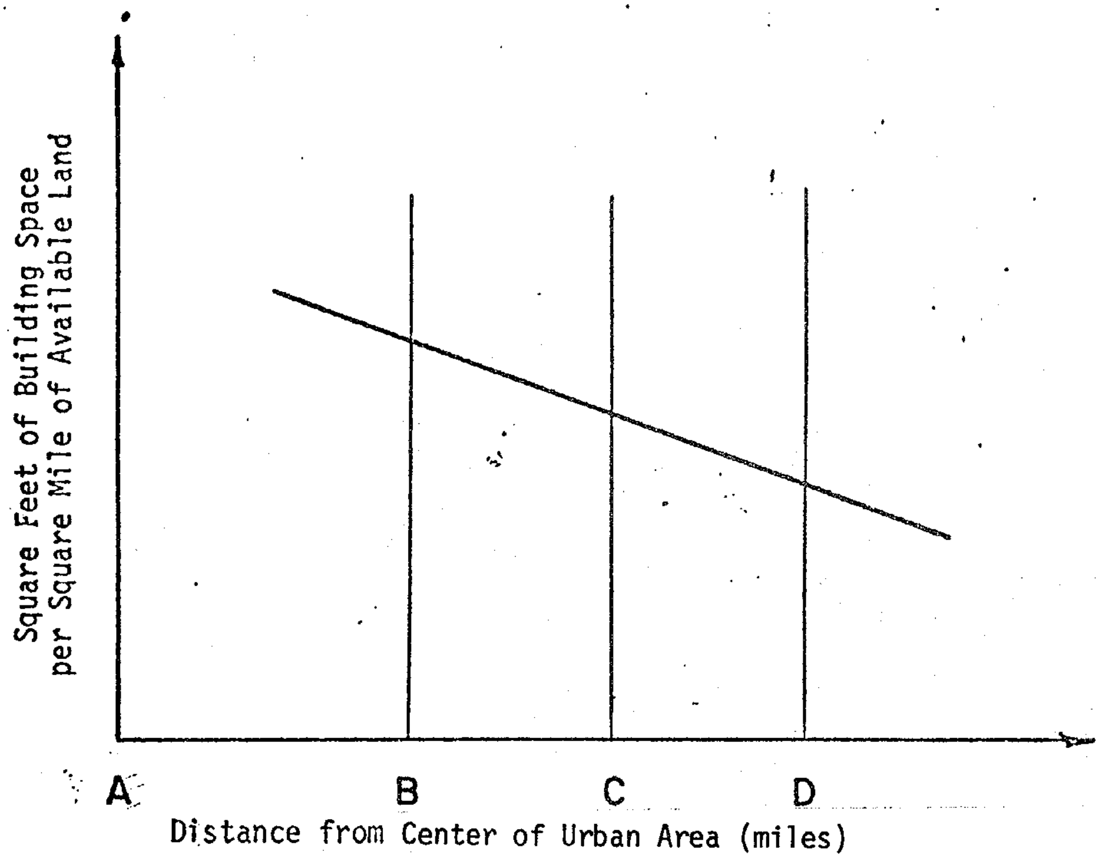

Figure 5 - Density of Building Space as a function of Distance from Center of Urban Area

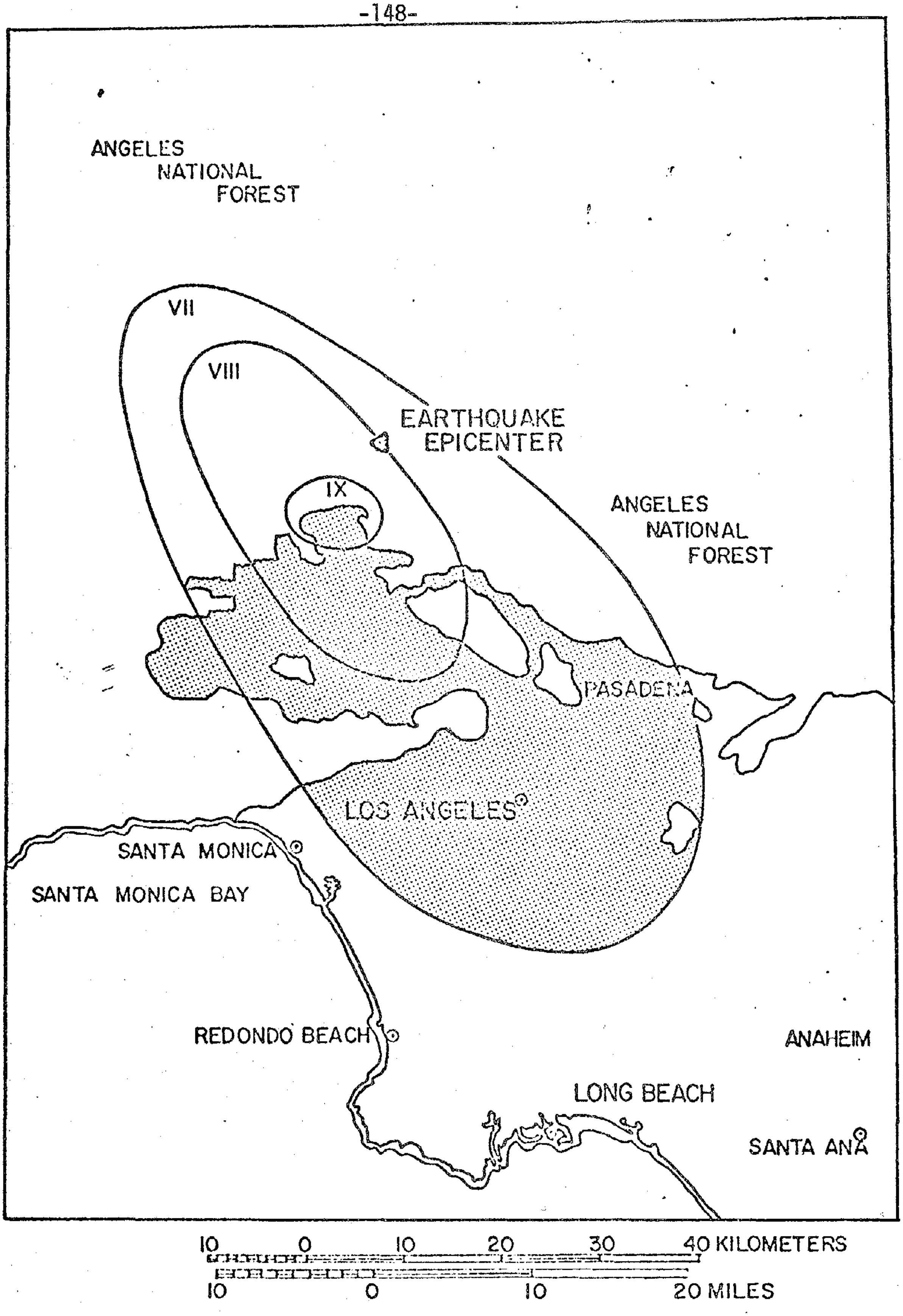

Figure 6. -The San Fernando, California, Earthquake of February 9, 1971; Zones of Modified Mercalli Intensity (Note: Shaded area represents urban area).

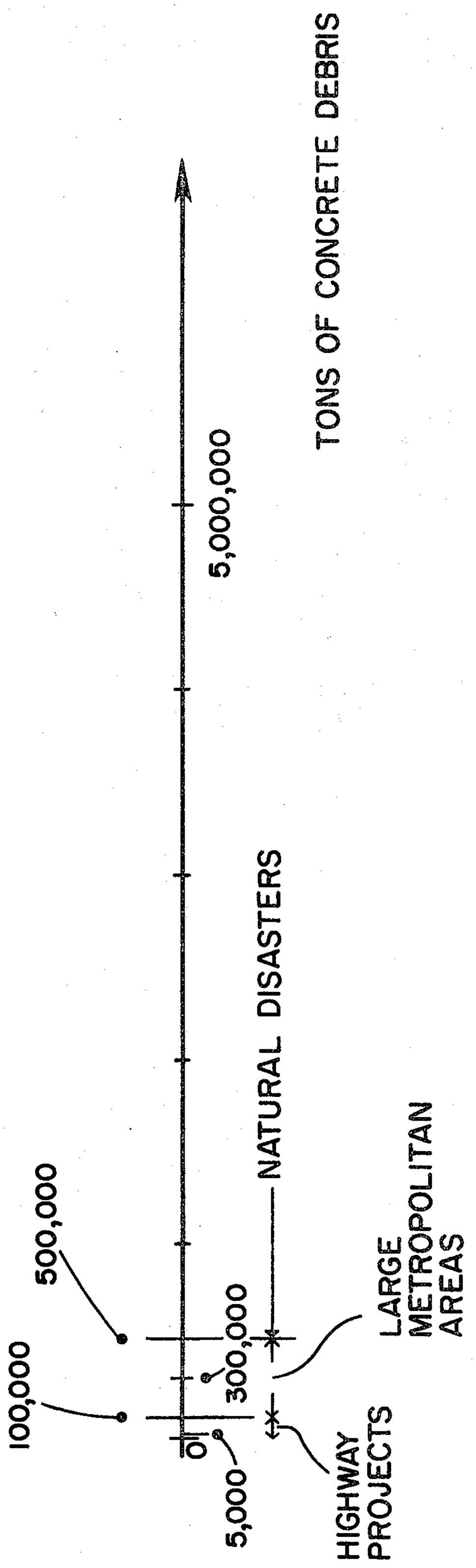

Fig. 7 - Concrete Debris Generation

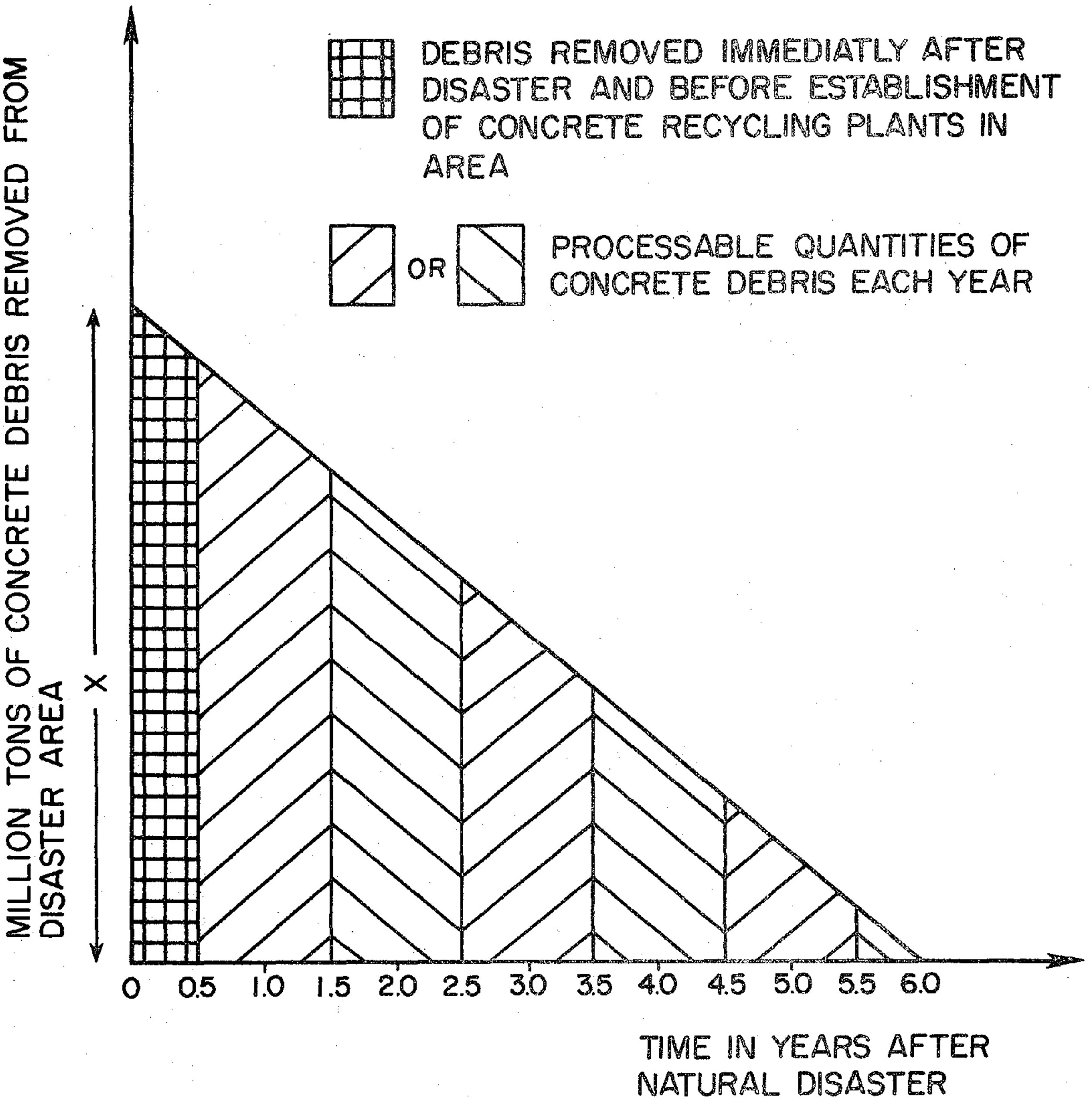

Fig. 8 - Clearance of Concrete Debris Following a Natural Disaster

Note: The area of the triangle in this Figure should equal the total tonnage of concrete produced by the natural disaster. Accordingly, the abscissa x varies from 0.167 to 3.30 million tons for total concrete debris generation of 0.5 to 10 million tons respectively.

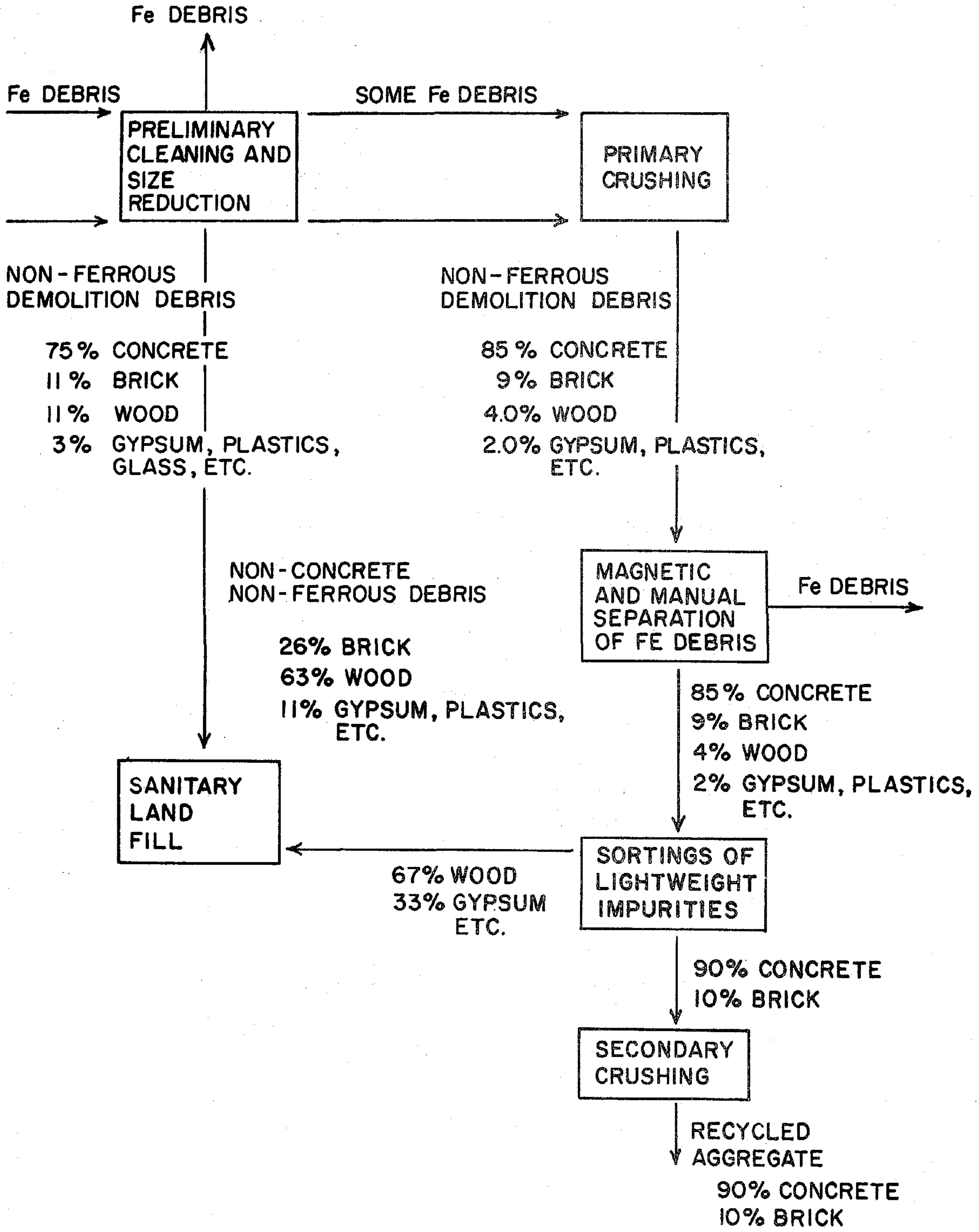

Fig. 9 - Material Balance of Plant for Recycled Concrete Aggregate.

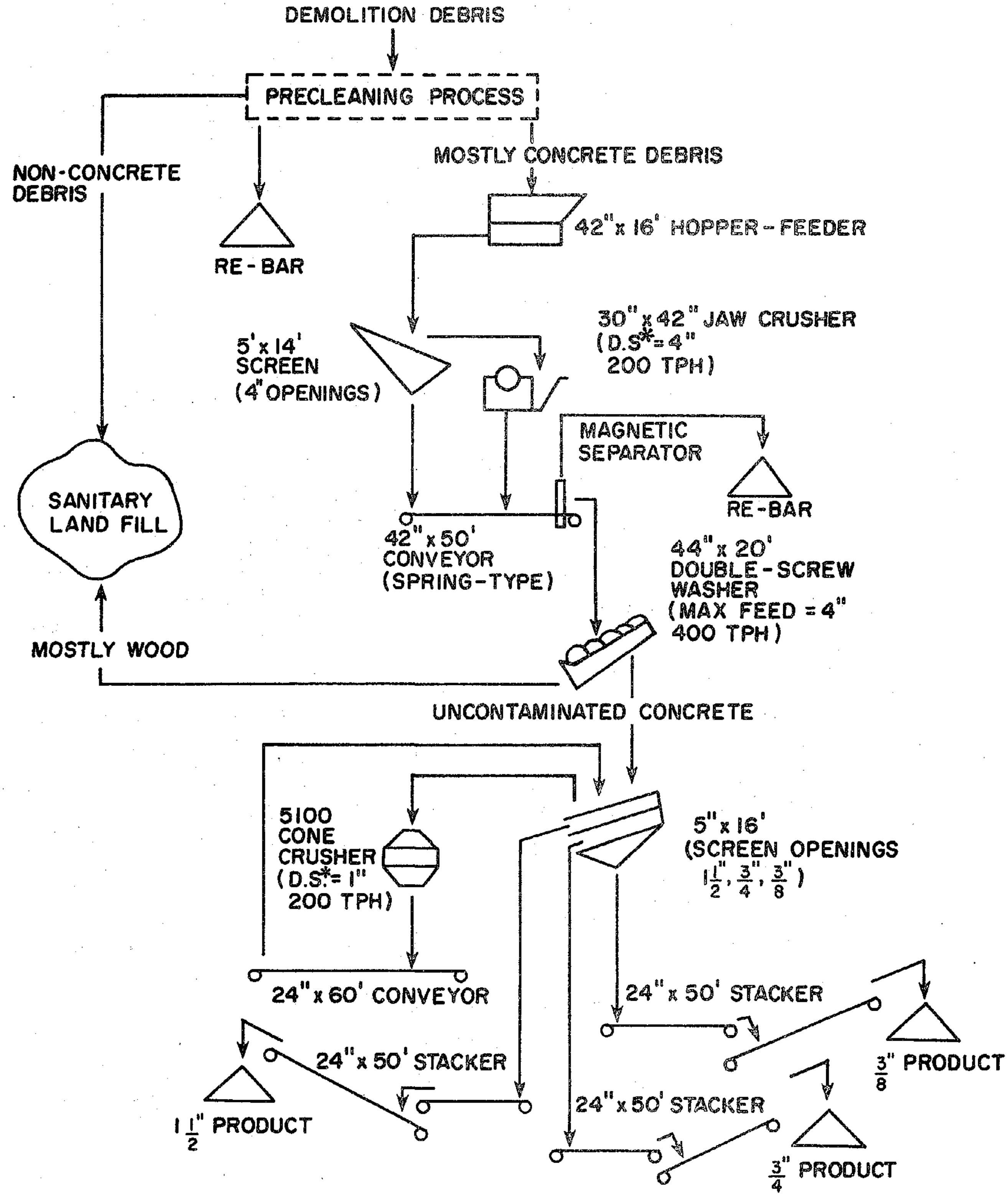

Fig. 10 - Schematic Design of a Recycling Plant with a 120-300 TPH Capacity
Note: D.S. = discharge.

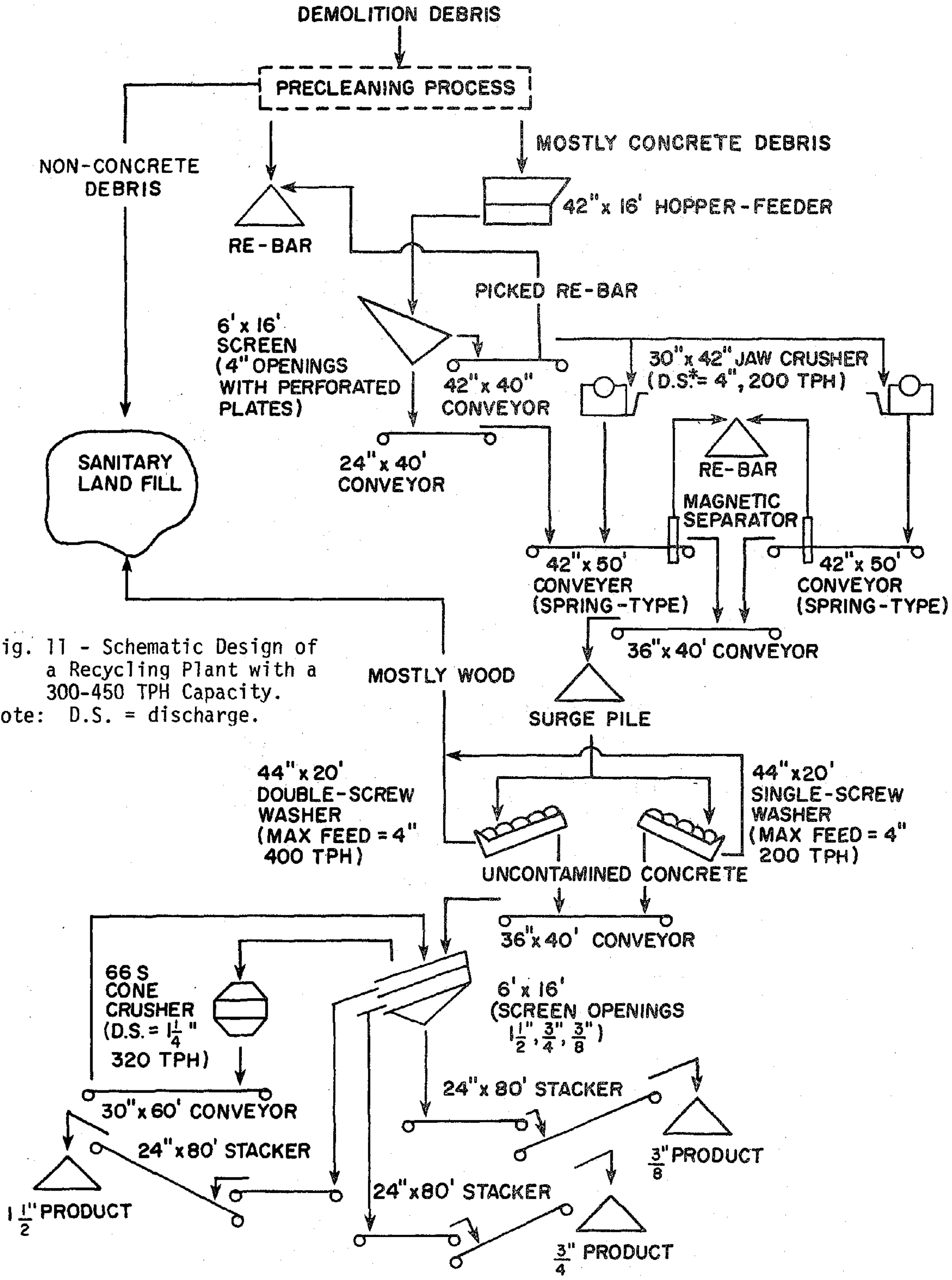

Fig. 11 - Schematic Design of a Recycling Plant with a 300-450 TPH Capacity.
Note: D.S. = discharge.

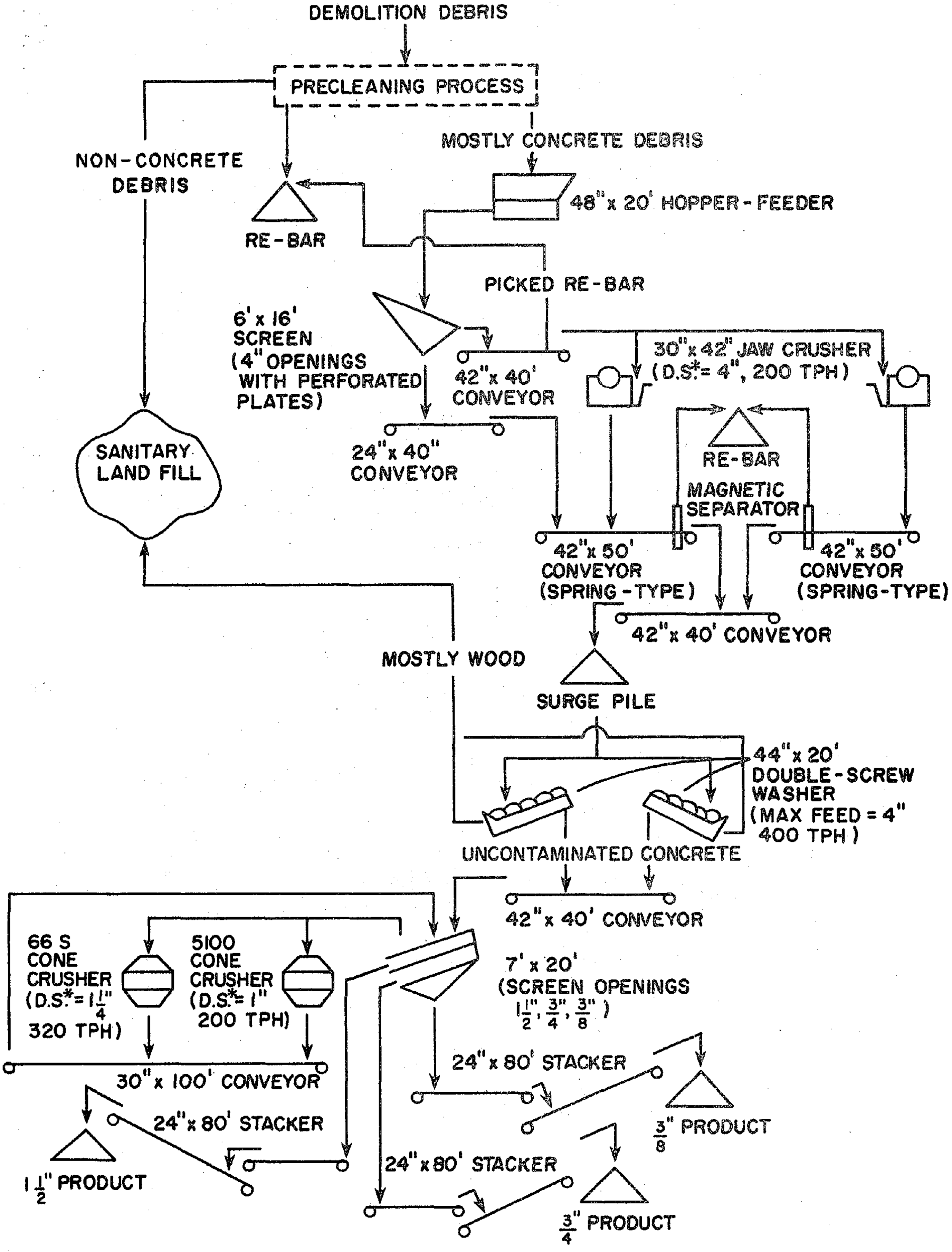

Fig. 12 - Schematic Design of a Recycling Plant with a 450-600 TPH Capacity.
Note: D.S. = discharge.

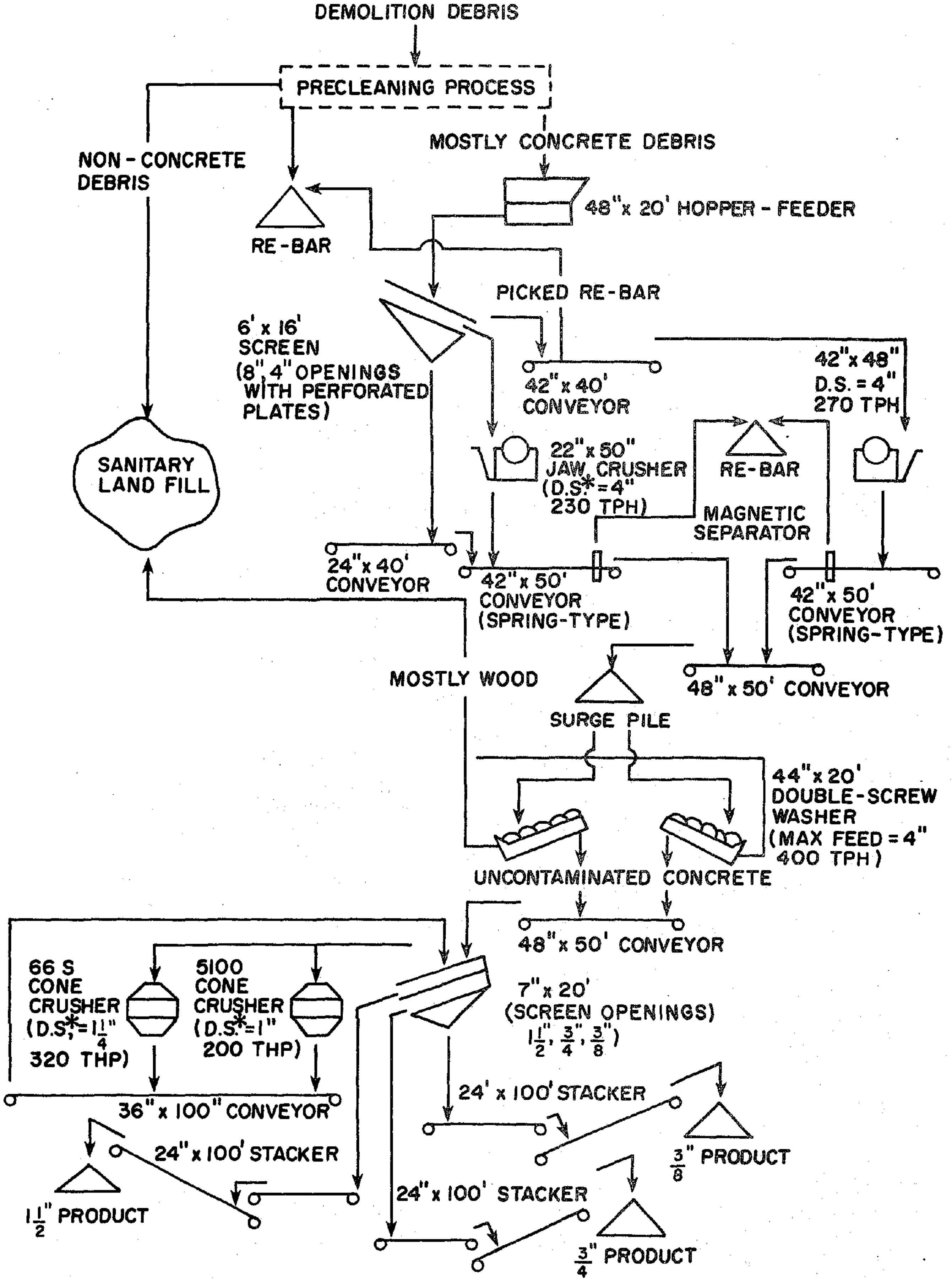

Fig. 13 - Schematic Design of a Recycling Plant with a 600-750 TPH Capacity.
NOTE: D.S. = discharge.

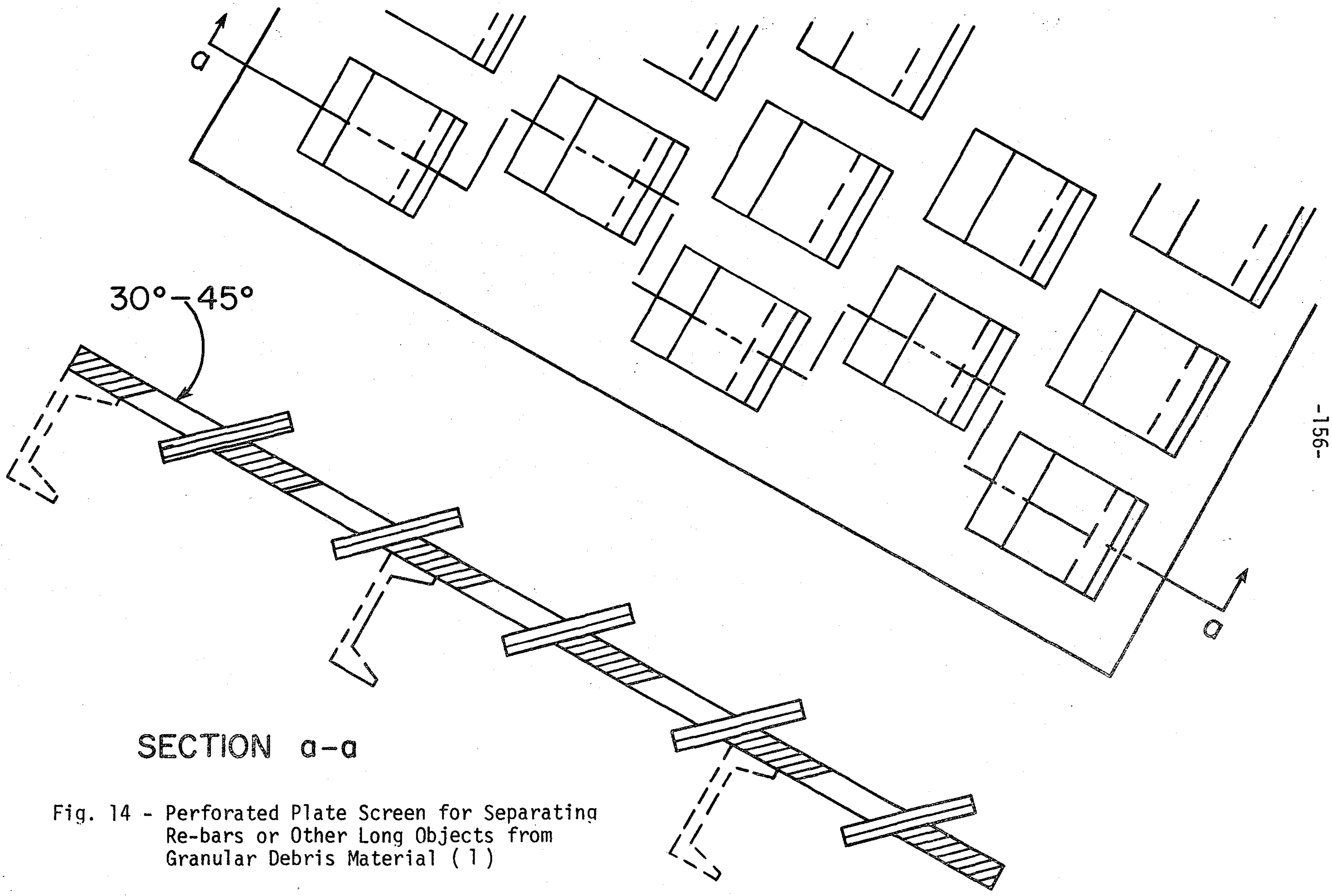

Fig. 14 - Perforated Plate Screen for Separating Re-bars or Other Long Objects from Granular Debris Material (1)

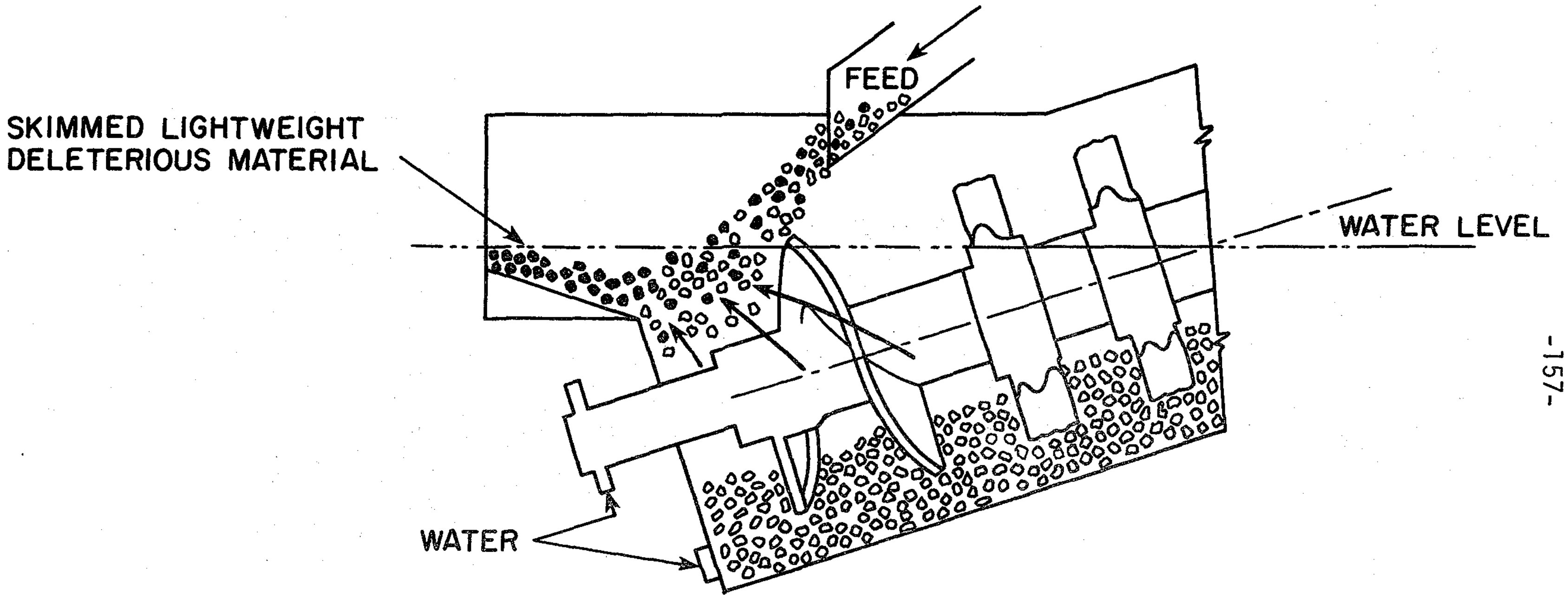

Fig. 15 - Operation of Coarse Material Washer (17)

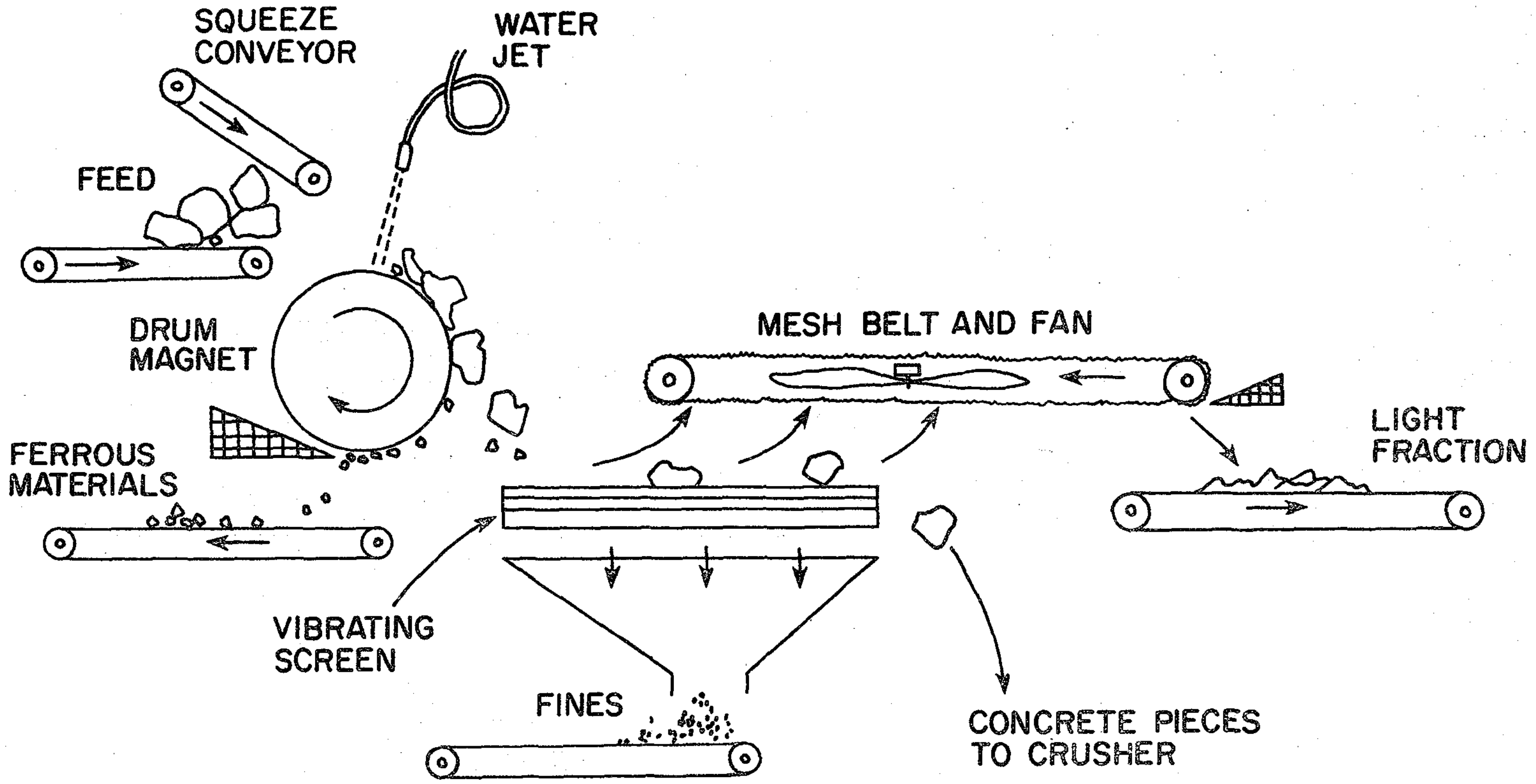

Fig. 16 - Preliminary Cleaning Operations (55)

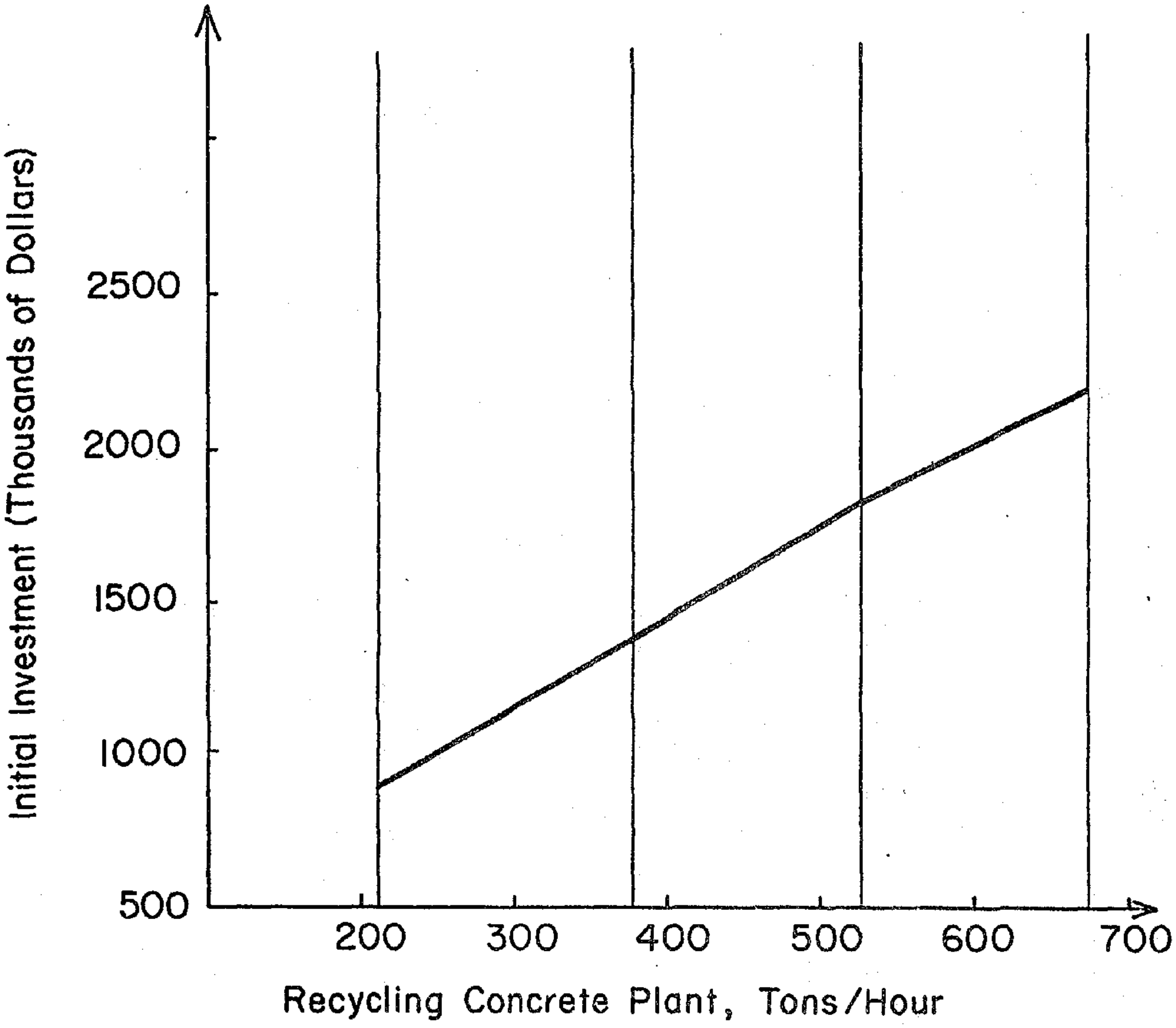

Fig.17. - Relationship Between Required Initial Investment in a Concrete Recycling Plant and Plant Capacity. (after Table 18).

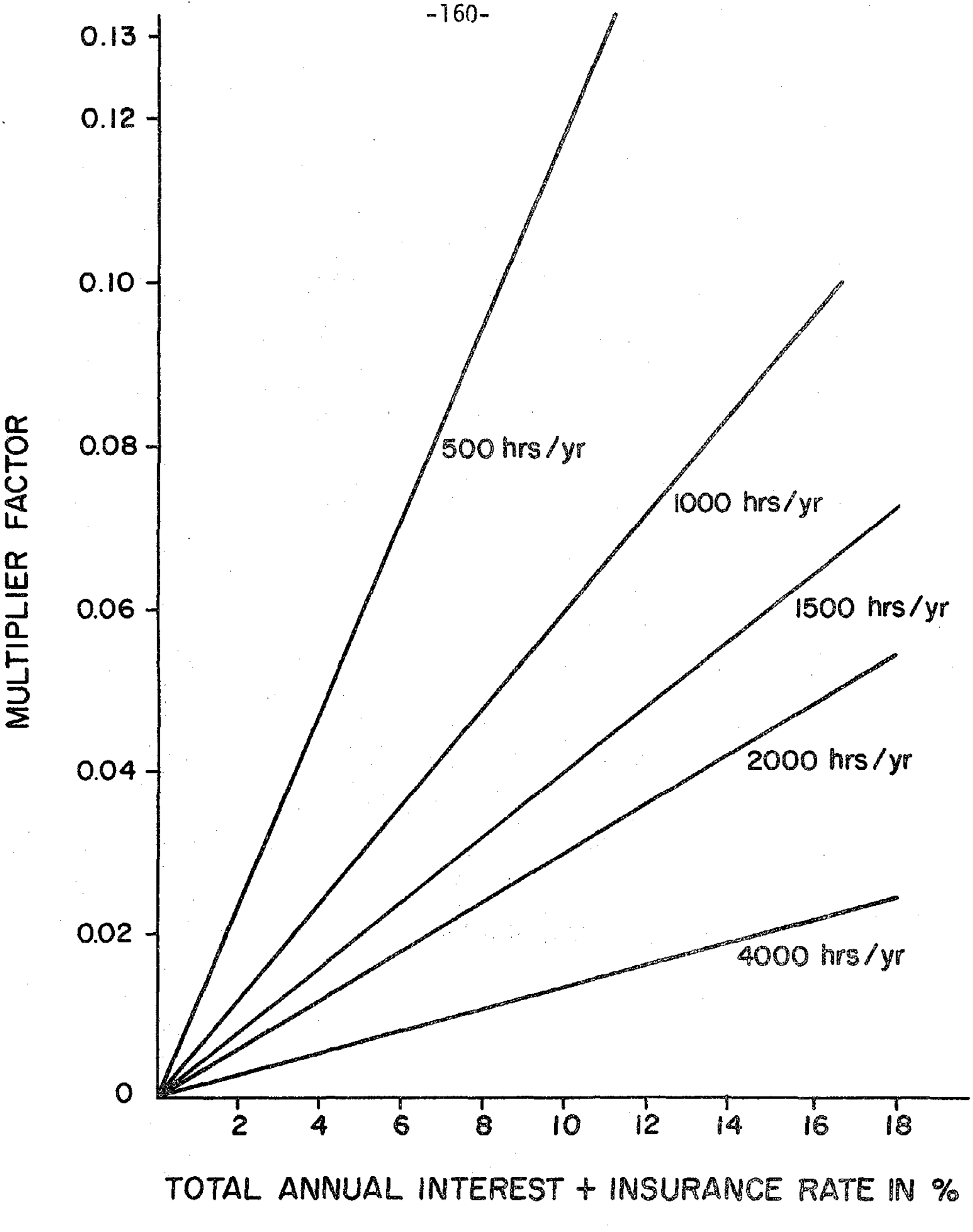

Fig. 18 - Guide for Estimating Hourly Cost of Interest and Insurance (22)

Note: Hourly cost = Multiplier Factor x Delivered Price / 1000.

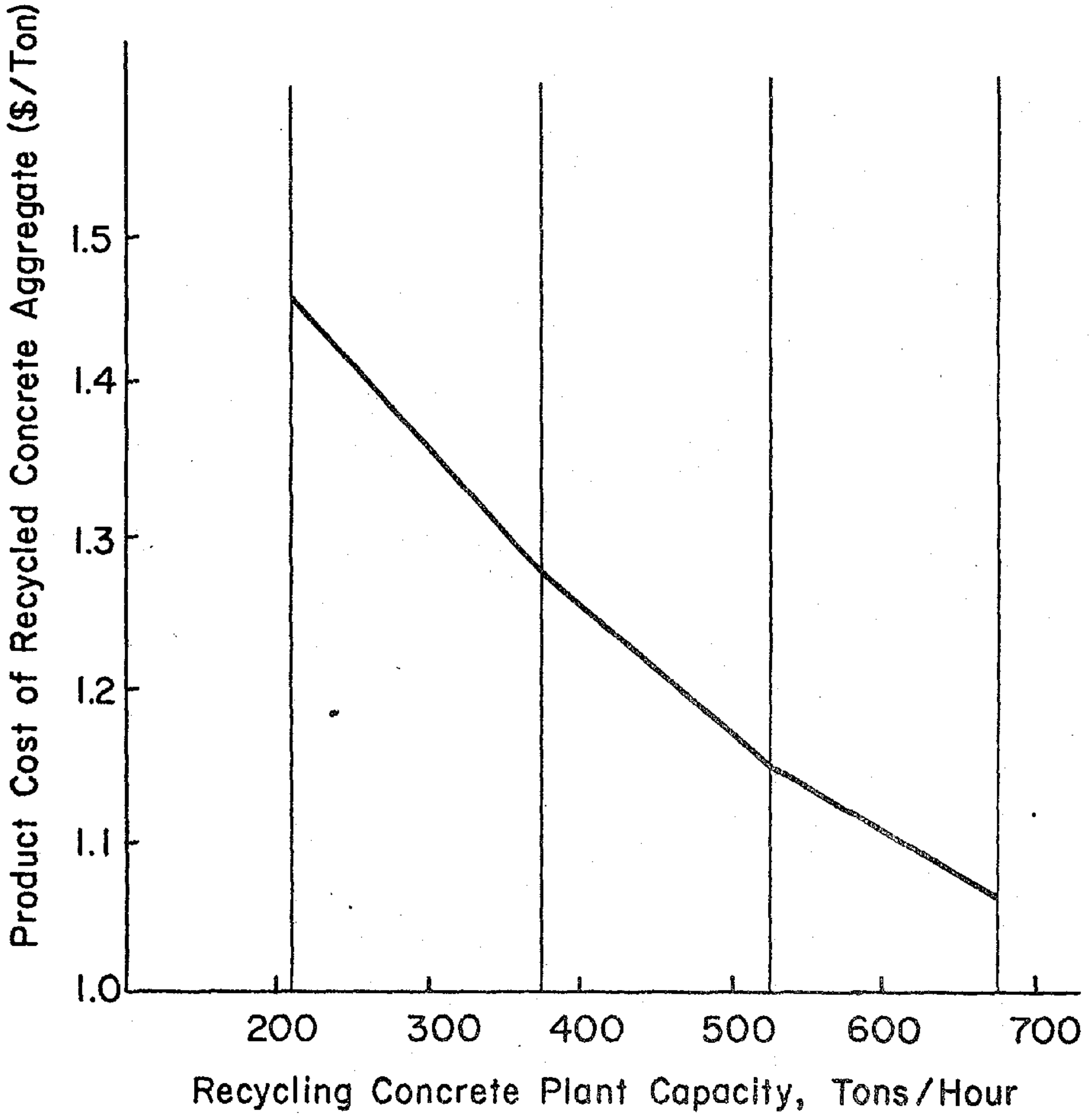

Fig. 19 - Relationship Between Production Cost and Plant Capacity in a Recycling Concrete Plant.
(Assumption: The plant operates 100 hours/year at average capacity and will be in operation for 4 years.)

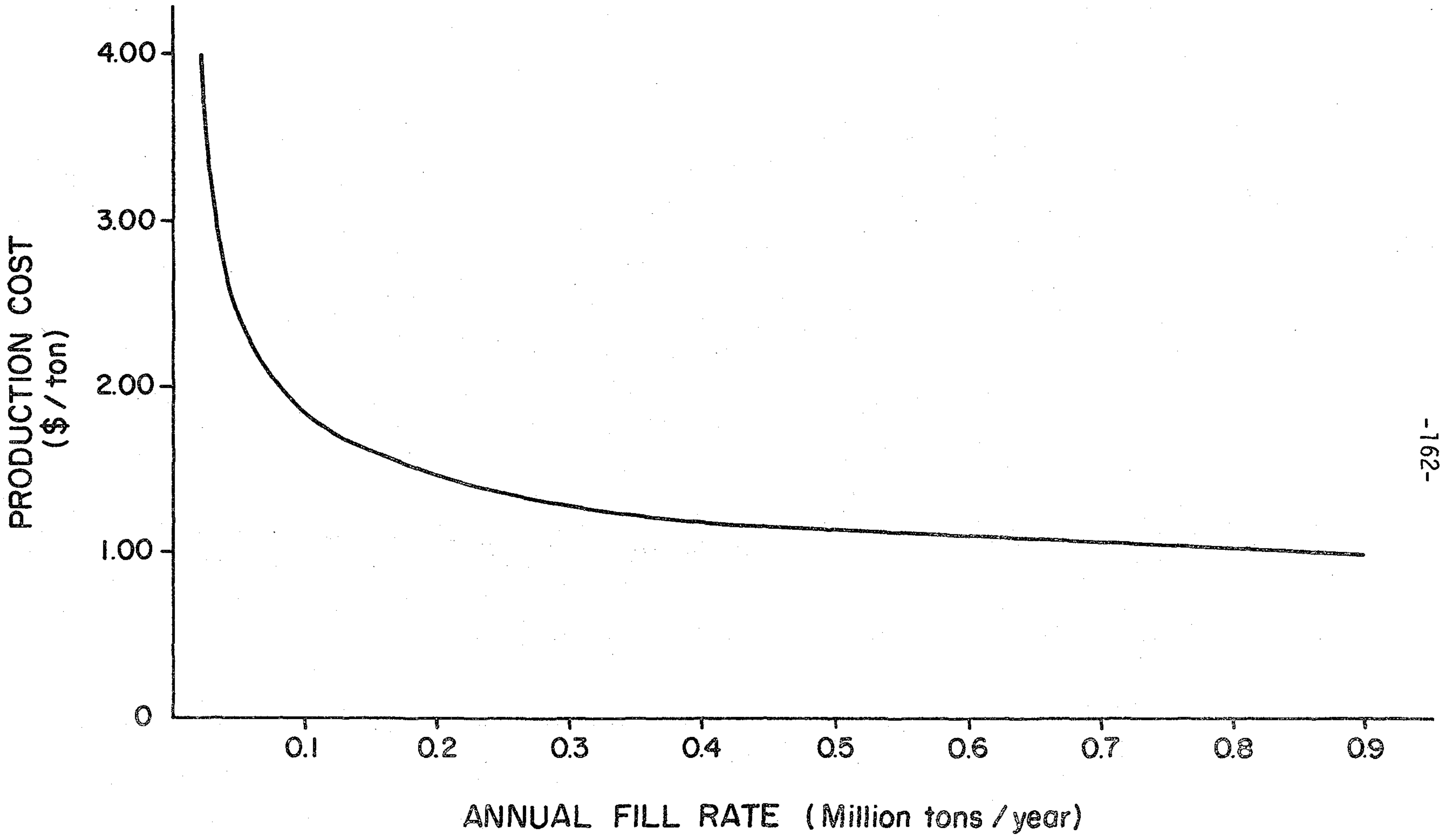

Fig. 20 - Production Cost of the SLF System (22)

APPENDIX I - NOTATION

The following symbols are used in this report:

C_3A = abbreviation for $3CaO \cdot Al_2O_3$. Tricalcium Aluminate.

DPM = Damage Probability Matrix

MMI = Modified Mercalli Intensity

RAC = Recycled Aggregate Concrete. Concrete in which crushed and graded waste concrete has been used as aggregate.

SLF = Sanitary Land Fill

UBC = Uniform Building Code

V = Volume of Specimen

W_a = Weight of the Specimen in Air

W_w = Weight of the Specimen in Water

γ = Specific Weight of the Water

APPENDIX II

ESTIMATE OF THE PERCENTAGE OF STRUCTURAL CONCRETE THAT NEEDS REPLACEMENT IN A HEAVILY DAMAGED BUILDING. SURVEY OF PROFESSIONALS IN THE AREA OF EARTHQUAKE ENGINEERING.

To estimate the percent of structural concrete that has to be replaced in a heavily damaged building we contacted seven distinguished professionals and scholars in the area of earthquake engineering and presented them with the following question, together with descriptive photographs.

QUESTION

The following question pertains to concrete-frame or concrete-shear-wall buildings of 5 to 20 stories.

From the following verbal description of a damage situation:

> Major structural damage requiring repair or replacement of many structural members; associated non-structural damage requiring repairs to major portion of interior; building vacated during repairs;

and the enclosed photographs describing visually the damage situation; and finally, a numerical description:

$$\frac{\text{cost of repairs}}{\text{cost of replacement}} = 0.3$$

Please estimate the percentage of structural concrete that needs to be replaced in this particular damage situation.

We received five replies with estimates ranging from 5 to 25% and an average value of 11.2%.

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

APPENDIX III - SOLICITATION OF ADVICE FROM EQUIPMENT PRODUCERS ON THE DESIGN OF CONCRETE RECYCLING PLANTS (LETTER)

February 17, 1977

Dear Sir:

I am a graduate student in the Department of Civil Engineering at Massachusetts Institute of Technology. I am currently working with Prof. S. Frondistou-Yannas on a National Science Foundation sponsored project which deals with an economic assessment of recycling concrete debris. In a previous study[1], the economic attractiveness of recycled concrete debris as a substitute for natural aggregate has been assessed for a processing plant with a 150 to 200 tph capacity. We now want to extend our investigation to higher capacities of the recycling operation. Also, we would like to deal more effectively with the problem of separating steel re-bars and wire meshes; wood; gypsum; and other deleterious materials from the concrete debris.

The purpose of this survey is to gather some realistic purchase/rental price and operational cost figures so that the production cost estimates can be made for concrete recycling operations. The latter, in this work, includes only the following operations:

(a) Preliminary separation of steel re-bars and wire-meshes from concrete debris.[2]

(b) Loading, crushing and screening through primary crusher.

(c) Further separation of steel re-bars and wire-meshes.[3]

(d) Loading, crushing and screening through secondary crusher.[4]

(e) Removing unwanted materials (e.g., wood pieces and gypsum in wallboards, plaster or tiles) from crushed concrete.[5]

(f) Stockpiling of finished product.

I would appreciate it very much if you could design in a rough manner a low-cost crushing-washing plant which would meet the following design criteria:

(a) The least expensive plant with respect to setting up and operating is preferred, whether fixed or portable.

(b) Primary crusher should be able to accomodate a maximum of a 3' x 3' concrete piece.

(c) Primary crusher should produce a 4" minus to 6" minus aggregate.

(d) Secondary crusher should procude a 1-1/2" minus aggregate.

(e) Average Production should be around ______ tph on continuous basis.

(f) Any model year equipment (new or used) can be used to assemble the plant.

(g) There is no spatial restriction upon the setting up of the plant.

The equipment which is possibly needed to construct the plant is listed on the next page. Please supply the figures requested if they are available; otherwise, please place a (?) in the appropriate box.

For equipment not available from your compnay, I would appreciate it if you could supply references from which we can locate it.

Attached you will find the diagram of a schematic design. Please feel free to change or modify the system.

In addition, I would like to ask you to enclose brochures describing the equipment you have used in the design.

If you wish to have a copy of our report, I would be more than happy to send you one. I would appreciate it if you would return this questionnaire as soon as possible. Thank you very much for your assistance.

Respectfully yours,

Herbert Ng

HN:D
Enclosures

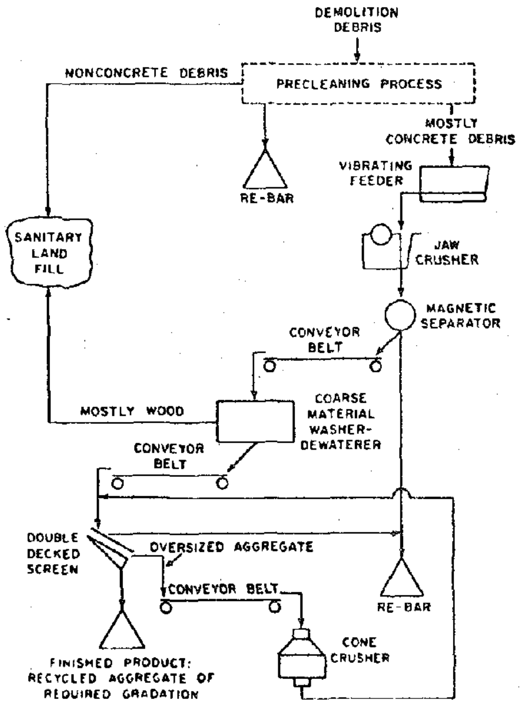
[1] Itoh, T., "An Assessment of the Economic Attractiveness of Waste Concrete as Aggregate Material," thesis presented to Massachusetts Institute of Technology, Cambridge, Mass., 1976, in partial fulfillment of the requirements for the degree of Master of Science.

[2] For example, size-reduction by steel ball hanging from a crane, then manual pick up of re-bar and wire-meshes.

[3] For example, a magnetic separator with some manual separation in addition.

[4] The 2-stage close-circuit process depicted in the attached figure can also be substituted by other processes.

[5] For example, a coarse material washer-dewaterer as shown in the attached figure, or an impactor type secondary crusher may serve some of the separation functions.


DEMOLITION DEBRIS
NONCONCRETE DEBRIS
PRECLEANING PROCESS
MOSTLY CONCRETE DEBRIS
VIBRATING FEEDER
RE-BAR
SANITARY LAND FILL
JAW CRUSHER
MAGNETIC SEPARATOR
CONVEYOR BELT
MOSTLY WOOD
COARSE MATERIAL WASHER-DEWATERER
CONVEYOR BELT
DOUBLE DECKED SCREEN
OVERSIZED AGGREGATE
CONVEYOR BELT
RE-BAR
CONE CRUSHER
FINISHED PRODUCT: RECYCLED AGGREGATE OF REQUIRED GRADATION

Please fill in the following Table. However, please do not hesitate to use any other format which is convenient to you.

Equipment	how many needed?	type and capacity or its size	unit purchasing price	unit. rental cost		estimated operating cost/hr. *	estimated M&R ** cost/month	expected economic life ***
				monthly	weekly			
1) primary crusher with engine								
2) secondary crusher with engine								
3) vibrating feeder								
4) double deck screen								
5) conveyors								
6) conveyor stacker								
7) generator								
8) loader (wheel)								
9) other major equipment A) FOR SEPARATING STEEL								
B) FOR SEPARATING WOOD AND GYPSUM								

* please exclude labor and depreciation cost

** M&R=maintenance & reparing

*** for the calculation of depreciation

Please indicate	1) labor requirement	2) estimated production rate on continuous basis
	A) loader operator ______ men B) crusher operator men	from ton/hour to ton/hour

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APPENDIX IV - REQUEST FOR CRITICAL REVIEW OF FINISHED DESIGN (LETTER TO EQUIPMENT PRODUCERS)

April 26, 1977

Dear Sir:

Thank you for the useful information that you have sent to us.

After spending some effort in analyzing the materials that we gathered, we finally came up with some tentative schemes for processing recycled concrete at different capacity ranges. Based on our objective, these schemes have to be technologically feasible, efficient, and produce products that can achieve some of our quality standards. Also, we have to be very aware of the economic feasibility of these schemes. Re-bar and metallic materials are the major factors affecting efficiency. We have tried to use a combination of pre-sorting at dump field, special screen, conveyor with spring adjustment underneath the jaw crusher, picking table and magnetic separator to minimize the problem. With regard to the quality standards, we are mostly concerned with the gypsum on the surface of the recycled concrete pieces, and wood materials. Coarse-material washer dewaterer has been selected after a review of some other types of washers, scrubbers and separation technologies.

Diagrams of these schemes, together with the price lists of the equipment used, are enclosed with this letter. We'll appreciate it very much if you can review these schemes and make some comments on their 1) feasibility, 2) efficiency, 3) ability to produce quality products and 4) economy. Also, we'll be grateful if you can check the prices and power consumption of the equipment used so that we will not present inaccurate information. Finally, we hope you can help us in evaluating the estimates of the operating costs (i.e., fuel and lubrication costs) and maintenance and repair costs of these schemes as presented on the last page of the enclosed materials.

Although we understand that our request may burden further your busy schedule, your suggestions and advice are valuable and indispensable in making this a fruitful study. Time is really pushing on us. It would be nice if we could hear from you at your earliest convenience. In case you may have questions, please contact me at 617-253-1000, Ext. 5-9562, or leave a message at 617-253-5336. We appreciate your help and look forward to hearing your comments in the near future.

Respectfully yours,

Herbert Ng

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Enclosures