

Recycling Concrete and Other Materials for Sustainable Development



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PREFACE

Recognizing the need to promote and encourage the use of recycled concrete and other materials in concrete construction, ACI Committee 555, Concrete with Recycled Materials, sponsored a two-part technical session on “Recycling Concrete and Other Materials for Sustainable Development” at the 2003 ACI Spring Convention in Vancouver, Canada. Twelve papers were presented by invited experts from Canada, Denmark, Japan, and the United States.

This Special Publication (SP) contains 11 of the 12 papers that were presented at the technical session. The subject areas include the global perspective, challenges and opportunities of concrete recycling, the barriers to recycling concrete in highway construction, and current practices in the European Union, Japan, and USA. This SP also contains research papers on the use of recycled glass as aggregates for architectural concrete, recycled scrap tire rubber, flowable slurry containing wood ash, recycled latex paint as an admixture, crushed stone dust in production of self-consolidating concrete, a new binder using thermally treated spent pot liners from aluminum smelters, and the durability of concrete containing recycled concrete as aggregates that had shown distress due to alkali-silica reaction. Each paper was reviewed by two reviewers in accordance with ACI publication policy.

On behalf of ACI 555, we would like to thank all authors for their contributions and the reviewers for their assistance, comments, and valuable advice. It is our hope that the success of this two-part technical session and the publication of this Special Publication will encourage the use of recycled concrete and other materials in concrete construction, and thereby help our industry to comply with the demands of sustainable development.

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Recycling Concrete—An Overview of Challenges and Opportunities

by E. K. Lauritzen

Synopsis: This paper consists of an overview of the development of techniques for recycling concrete. Demolition, processing and the recycling of the resulting materials are often analyzed separately. “High quality” recycling of concrete waste does not always correspond to production/use of the product with the highest value, but rather the most feasible product in a specific project or region. It is by analyzing the whole disposal/supply-chain, including the substituted material, that the best effects of recycling can be achieved.

Overviews of methods for environmental evaluations as well as economic considerations are presented. Integrated demolition waste management in Kosovo and an analysis of the potential market in Hong Kong are presented as examples of the worldwide market for recycled materials. Issues regarding the handling of polluted materials will be discussed from a practical point of view. Moreover, some aspects to consider regarding future demolition when producing new concrete products are presented.

Keywords: concrete; construction and demolition waste; demolition; integrated waste management; recycling

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SUSTAINABILITY AND “GREEN” CONCRETE

Since Agenda 21, the Rio Declaration on Environment and Development, was launched in 1992 sustainable development has been one of the key issues of modern society. Some years ago, ACI realized that even if concrete is an environmentally friendly material, Portland cement is the critical component of modern-day concrete. To address this issue and the relationship between sustainable development and concrete technology, the ACI Board of Direction, in 2000, formed a Task Group on Sustainable development and concrete technology. Its mission was to encourage the development and application of environmentally friendly, sustainable concrete materials, design and construction. One of the most important issues of sustainability was the use of recycled aggregates (1).

Fortunately, some ACI members had been far-sighted enough in 1985 to organize Committee 555 – Concrete with Recycled Materials. In 2001 the committee submitted a report *“Removal and Reuse of Hardened Concrete”* (2), which has established a very good basis for the future work of ACI on the sustainability and recycling of concrete.

Parallel to the work of ACI in the USA, the recycling of Construction and Demolition waste (C&D waste) has emerged as a socio-economic priority within the European Union and a considerable amount of research and development has taken place in the frame of RILEM¹. In 1981 European and Japanese members of RILEM took the initiative to complete the first RILEM technical committee on the demolition and recycling of concrete, including several material research projects in this field. The research of the RILEM technical committees on recycling has been published in proceedings from three international symposia held by RILEM in Antwerp, Belgium 1985 (3), in Tokyo, Japan, 1988 (4) and in Odense, Denmark, 1993 (5). In 2000 the state-of-the-art-report of RILEM Technical Committee 165-SRM on *Sustainable Raw Materials* was edited by C.F. Hendriks and H.S. Pietersen (6).

THE NEED FOR C&D WASTE MINIMIZATION

In all communities it has always been common practice to retrieve valuable materials from the arising waste, e.g. metals and building materials. After some decades in this century with an extensive “use-and-throw-away” philosophy it has been recognized that we cannot continue this uninhibited use of natural resources and pollution of the world

¹ **RILEM** : The international union of testing and research laboratories for materials and structures

with waste. It is necessary to change our habits and to revise former common practices within the building & construction industry, as well as within other industries, households etc.

In many countries, industrial as well as developing, C&D waste is considered as harmless, inert waste, which does not give rise to problems. However, C&D waste consists of huge amounts of materials that are often deposited without any consideration, causing many problems and encouraging the illegal dumping of other kinds of waste. Whether C&D waste originates from clearing operations after natural disasters or from human-controlled activities, the utilization of such waste by recycling can provide opportunities for saving energy, time, resources and money (7, 8, 9). Furthermore, recycling and the controlled management of C&D waste will mean that less land is used and better opportunities will be created for the handling of other kinds of waste.

C&D WASTE STREAMS IN THE EU AND USA

A large proportion of C&D waste derives from demolition, rehabilitation, and new construction following normal development, as well as from natural and technological disasters. For example, the production of building materials and goods involves surplus ready-mixed concrete, concrete elements, articles of wood etc., which can be classified as industrial waste.

In the European Union, whose population in 2000 was approximately 370 million, it is estimated that the annual generation of C&D waste is approximately 200- 300 million tonnes - equivalent to $\frac{1}{2}$ - 1 tonne per capita per year in very rough figures (7, 10).

Clear figures regarding recycling do not exist in every EU member country. An EU study calculated that an average of 28 % of all C&D waste was recycled in the late 1990s (11). In the Netherlands 95 % of all C&D waste is recycled and in Denmark 90 % is recycled.

Most EU member countries have established goals for recycling that range from 50 % to 90 % of their C&D waste production, in order to substitute natural resources such as timber, steel and quarry materials. Recycled materials are generally less expensive than natural materials, and recycling in Germany, Holland and Denmark is less costly than disposal (7, 10, 11).

The C&D waste streams in the USA were assessed by Robert H. Brickner in 2002 (12). It is estimated that the amount of C&D waste is 250 – 300 million tonnes per year (2002 figures) and that 20 – 30 % is recovered for recycling (1996 figures).

According to Metha (13) the global concrete industry uses approximately 10 billion tonnes of sand and rock each year and more than 1 billion tonnes of C&D waste are generated every year.

CHALLENGES OF RECYCLING

According to the EU Waste Directive on Prevention and reduction of Waste the key issues are:

- Cleaner technologies
- Recycling, reuse & recovery (R3) of waste
- Management and planning of CDW handling
- Polluter pay principle

This presentation will focus on recycling. C&D waste has a high recycling potential because the majority of it consists of masonry, concrete, and steel. In Europe up to around 90 % of C&D waste consists of concrete and masonry. Buildings erected before the middle of the last century were mainly constructed with masonry, and buildings in the second half of the century were mainly constructed with concrete. The situation in the USA is probably the same.

Based on a global overview (13) it is estimated that the potential of recycling is approximately 50 %, which is equal to approximately 500 million tonnes, which is equal to 5 % of the global consumption of sand and rock.

At present, only very limited amounts of C&D waste are recycled as high-value materials, such as recycled aggregates in new concrete. The majority of such waste is disposed of or used as fill. Since the amounts of C&D waste are constantly increasing, there are many reasons for focusing on methods that promote an increase in the recycling of C&D waste (dumping fees in Europe and the USA are typically from US\$ 20-50 per tonne). Present results in Europe show very favorable recycling possibilities in this field.

From a purely economic point of view the recycling of building waste is only attractive when the recycled product is competitive with natural resources in relation to cost and quality. Recycled materials will normally be competitive where there is a shortage of both raw materials and suitable deposit sites.

With the use of recycled materials, economic savings in the transportation of building waste and raw materials can be achieved. In larger recycling projects, such as urban development, renovation of motorways, or clearing of war/disaster-related damages, the total project cost will be dominated by transportation costs. These transportation costs involve the removal of demolition products and the supply of new building materials. In these cases the use of recycled materials is very attractive.

The prospects of systematic recycling of C&D rubble in various parts of the world have been analyzed (7, 14). In order of importance, the three main factors affecting the prospects of recycling C&D waste are

- population size and density,
- occurrence of and access to natural raw materials, and
- level of industrialization.

OPPORTUNITIES FOR RECYCLING

In order to meet the challenges of recycling, it is necessary that all opportunities, barriers and obstacles are detected and considered. The opportunities must be exploited, which can for example involve the recycling of concrete and masonry into aggregate, substituting natural materials:

- Aggregate bound in concrete
- Unbound sub-base and base materials

The opportunities for the production of concrete from recycled concrete are generally described in the ACI 555 report (2), and the recycling of concrete waste in a global perspective is described by Torben C. Hansen and Erik K. Lauritzen (7), Mats Topping (15) and Mats Topping and Erik K. Lauritzen (16).

The overcoming of these barriers and obstacles must be planned and carried out through a long-term action plan combined with adequate research and development.

Implementation of the necessary legal, economic and technical instruments requires that initiatives involving legislation and regulations be taken.

Economy

With a condition of market economy, the choice between recycled and natural materials depends on price and quality. The quality of concrete with recycled aggregates can be the same as that of concrete with natural aggregates, but recycled concrete aggregates are regarded with suspicion. Hence, recycled concrete materials will only be preferred where the price of such aggregates is considerably lower than that of the natural materials, even when the recycled aggregates meet given specifications.

Introducing economic instruments, which encourage recycling and the use of recycled materials, can overcome the economic barriers. As an example it should be mentioned that several countries have introduced special taxes and fees in favor of recycling. For example, in 1986 the Danish government introduced a tax on waste that is not recycled but disposed of at landfill sites. Today the tax is DKK 375 (approx. EURO 50) per tonne of waste disposed of at landfill sites.

The major issue of the cost-benefit to society is:

- willingness to pay for the impact on the environment
- willingness to accept the impact on the environment

Policies & Strategies

C&D waste must be considered as a specific individual type of waste associated with the building and construction industry. It is important that the management and handling of waste is carried out by the industry itself. Generally, the building and construction industry is relatively conservative, and changes in normal procedures often take time and need long-term policies and strategies.

One of the most important barriers is the many different interests in building waste

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Usually it is the environmental politicians, departments and public offices who prepare the policies and issues concerning waste recycling and reduction, whereas the building and construction industry is controlled by laws, departments and offices concerned with housing, construction and public works. To co-ordinate the interests of all parties, particularly with respect to the implementation of cleaner technologies in industry, it is necessary that long-term policies and strategies should first have been prepared and implemented.

Danish experience in this field has led to the recommendation that long-term strategies, e.g. for 10 years with respect to achieving goals for the recycling of C&D waste, should be adopted. These must then be continuously revised in accordance with the political situation, and followed up by adequate legislation and regulation at all levels - national, regional and local.

Certification of recycled materials

Demolition and crushing techniques for the production of recycled materials are well known and based on existing technologies. However, some changes in the demolition process, compared with traditional demolition, are required as described below. Even when recycled materials fulfil current standards for natural materials, and even when the prices can compete with the prices of natural materials, certain barriers still exist.

Owing to tradition and psychological barriers the general attitude towards recycling in the building and construction industry is largely prohibitive towards the utilization of recycled materials. Therefore, it is of great importance that recycled materials are officially certified and accepted by all parties in the building and construction industry. For example, in June 1994 RILEM published recommendations for concrete with recycled aggregates (17). A review of international classification and certification of use of recycled C&D waste is presented by Henriksen (10).

It is recommended that considerable emphasis be placed on specifying the areas of utilization and quality standards for recycled materials. These must be in accordance with the local demand in order to improve confidence in the recycled materials and solve problems regarding the responsibility of using such materials.

Planning demolition projects

A necessary condition for the recycling of building waste is careful sorting of the waste. Waste from new constructions and rehabilitation is sorted either at the production site or at a special treatment site. This separation into materials categories is fairly simple.

The sorting of waste from demolition is, however, a more complicated process. Demolition has until recently been regarded as a low technological process. Rapid demolition and disposal of structures were the main aims of the contractor. Special measures to separate the different types of materials were not possible, owing to the time factor, nor were they desired.

Optimal handling and recycling of C&D waste depends on the materials being sorted in-situ and in co-ordination with the demolition process using demolition technologies and methods as described in the ACI 555 report (2). It is therefore necessary to alter the traditional methods of demolition and introduce selective demolition. This requires that before and during the demolition process an effective sorting of the different materials categories is carried out, thereby preventing any mix of materials leading to pollution of, for instance, recyclable concrete/masonry rubble by wood, paper, cardboard, plastics etc. Since selective demolition takes more time than traditional demolition, detailed planning is considered as mandatory.

It is recommended that demolition projects should be planned and controlled in detail, in the same way as all other building and construction projects, to ensure selective demolition and correct handling of the demolition waste.

Education and information

The most important means to identify and exploit the opportunities and overcome the barriers and obstacles is education and information. It is necessary that the message and understanding of recycling be discussed at technical universities, among private enterprises and public servants.

INTEGRATED RESOURCE MANAGEMENT

In order to achieve the maximum benefit of recycling a management system must be established on a project basis in relation to a specific construction project, e.g. urban development master plan, or on a permanent basis in relation to long-term municipal and C&D waste management system.

The Integrated Resource Management System comprising environmentally and economically balanced management of the following elements:

- Demolition (selective demolition)
- Recycling, reuse recovery
- Handling of hazardous C&D waste materials and non-recyclable materials
- Transportation
- Substituting (saving) natural resources

A presumption of the success of the Integrated Resource Management System is that an effective co-operation between all stakeholders/decision makers has been established in order to avoid a conflict of interests. Conflicts between recycling companies and raw materials companies, for example, could prevent all initiatives towards recycling in general.

The Integrated Resource Management can be implemented according to normal routines of project management in the construction industry, e.g.:

- National policies (legal and fiscal instruments)

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- Regional strategies (control of C&D streams, stationary or mobile recycling plants)
- Concepts (high versus low value recycling)
- Feasibility studies (specific proposals for recycling)
- Computer optimization (e.g. waste-resource streams and economic models)
- Master planning
- Design
- Supervision
- Quality & environmental management

GLOBAL VISIONS

The construction industry must aim at durability and sustainability as described by Metha (13). A holistic life cycle based approach is recommended in order to reduce the environmental impact. Further it is mentioned that the resource efficiency of the concrete industry will increase by a factor of five if the service life of most structures built today were 250 years instead of the conventional 50.

Looking at recycling, it is estimated - based on a global C&D waste production of 1 billion tonnes per year - that potentially 50 % should be recycled and could substitute approximately 5 % of the global consumption of sand and rocks.

However, the truth is that there is a long way to go before this level of recycling can be attained in developing countries, and many other environmental problems must be prioritized. But there is no excuse for the industrialized nations not to start the implementation of Integrated Resource Management Systems, aiming of 90 % recycling and maximum substitution of natural resources. There is no doubt that results and experience from European research and development can be transferred to other parts of the world and enable natural (primary) raw materials to be replaced by recycled materials, especially in urban renewal and rehabilitation projects.

CONCLUSION

The development of technologies for the recycling of concrete and the market for various types of recycled concrete materials has proved the viability and sustainability of recycling concrete. The challenges of recycling are dominated by a very high potential of concrete waste all over the world and a demand for recycled materials in order to substitute natural resources. The opportunities for recycling are based on economics, policies & strategies, certification of recycled materials, planning of demolition projects, and education and information.

The success of recycling concrete today in some European countries is based on integrated resource management. The success of recycling in the future is based on global visions for the implementation of recycling concrete worldwide in order to save natural resources and protect the environment.

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Recent Trends in Recycling of Concrete Waste and Use of Recycled Aggregate Concrete in Japan

by Y. Kasai

Synopsis: This paper addresses first the generation of construction waste in Japan, the extent of recycling, and the shortage of landfill capacity. Second, it chronicles the trend of recycling concrete rubble from 1970 until today. Third, it discusses methods of manufacturing recycled concrete aggregate and introduces the recently developed equipment and methods to produce good aggregate for concrete. Fourth, the problems associated with the use of recycled concrete aggregate are mentioned. Also, the utilization of concrete fines, eco-concrete, and slurries from ready-mix concrete plants are addressed. Land in Japan is very scarce and resources limited. These conditions are similar to those faced by Europeans and Scandinavians. Therefore, this paper should be of interest to those countries and their efforts to build closed-loop material cycles.

Keywords: concrete waste; construction waste; Japan; recycled aggregate; recycled concrete

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INTRODUCTION

Japan generates about 35 million tons of concrete debris each year. The productive use of this material is very important for the establishment of a sustainable society. This paper addresses the following issues:

1. Generation of construction wastes and their reuse as a resource.
2. Shortage of landfills suitable for industrial waste material.
3. Outline of construction recycling law.
4. Progress made in recycling and reuse of concrete as aggregate.
5. Methods of manufacturing recycled concrete aggregate.
6. Technical Report TR A0006, "Recycled Aggregate Concrete".
7. Problems with quality of recycled concrete.
8. Uses of recycled aggregate concrete.
9. Recycling of concrete rubble for road base and back fill.
10. Use of concrete powder, eco-concrete, and slurries.

The paper mentions the importance of recycling concrete wastes, the methods of producing good recycled aggregate using newly developed equipment and production processes, and problems associated with using recycled concrete in actual construction projects.

GENERATION OF CONSTRUCTION WASTES AND THEIR REUSE AS A RESOURCE

Starting in the fiscal year 1990, the Ministry of Land, Infrastructure and Transport has been conducting nationwide surveys of generation and reuse of construction wastes. The results are shown in Table 1. They show the amount of waste material associated with new construction and demolition, where concrete and asphalt rubble and construction waste wood appear to be due mainly to demolition.

In fiscal year 2000, about 85 million tons of construction waste material was generated, which was 14 million tons less than in fiscal year 1995. The breakdown of this decrease is as follows: 6 million tons of asphalt concrete rubble, 2 million tons of construction mud due to a reduction in public works projects, and the remainder due to reductions in other categories, including the effect of separation and reuse. Fig. 1 illustrates changes in the recycling rate during the ten years, from 1990 to 2000. The recycling rate for concrete rubble has improved from 48% in 1990 to 65% in 1995 and 96% in fiscal year 2000. The recycling rates for asphalt concrete rubble in the same years were 48%, 81%, and 98%,

respectively. For construction mud, the corresponding recycling rates were 8%, 14%, and 41%, mainly due to improvements of plants for dewatering/caking and soil improvement.

The recycling rates for construction wood waste were 31%, 40%, and 38%. This comparably poor showing resulted in spite of recycling of wood as cement-bonded wood particle boards and pulp for paper production. The remainder was used as fuel or incinerated and disposed of illegally.

SHORTAGE OF SAFE LANDFILLS FOR INDUSTRIAL WASTE

Construction waste constitutes about 22% of the 400 million tons of all industrial waste. Landfill sites that remain available for such waste material have decreased year by year, which poses a big social problem. It has become particularly difficult to build new treatment plants in the face of opposition by nearby residents because of the environmental impact. Fig. 2 illustrates the number of permanent landfill sites permitted for industrial waste from 1987 to 2000, while their combined capacities are plotted in Fig. 3 and their remaining life (in years) is indicated in Fig. 4. In fiscal year 2000, the remaining landfill capacity was 176 million m³, to last for 3.9 years.

Although the remaining landfill capacity decreased and the remaining life increased, the generation of waste decreased over the same time span. Landfill capacity for industrial waste material became so sparse that the government used this opportunity to promote two slogans: “Controlling the generation of waste and decreasing its amount” and “Creating a closed-loop material cycle society”.

Fig. 5 illustrates the projected developments of production, waste disposal, and accumulation of building stock during the next hundred years. According to this estimate, the total amount of waste will be four times as great as it is today.

Finally, on May 30, 2002, the Japanese Government decided to enforce the “Law on Recycling of Materials in the Construction Industry, etc”, now called the “Construction Recycling Law”.

OUTLINE OF THE CONSTRUCTION RECYCLING LAW

The “Construction Recycling Law” is based on the “Law to Promote Effective Recycling of Resources”, or “Recycling Law”, formulated in 1991 and enacted to further promote recycling of construction related resources. This law refers specifically to concrete rubble, asphalt concrete rubble and construction waste wood.

Conventionally, the owner used to submit to the governor a demolition plan, indicating the type of structure and floor area of the building. However, the new law requires the owner to submit a “Notification Document” for any planned generation of waste in the following cases:

1. Demolition of a building with a floor area greater than 80 m².

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2. New construction with a floor area greater than 500 m².
3. Expansion, repair or remodeling of a building costing more than 100 million yen.
4. Public works projects exceeding a cost of 5 million yen.

It is assumed that each of the last three cases generates the same amount of waste as case 1, which is estimated to be about 30 to 40 tons per house.

The notification document should include various characteristics of the construction, such as the usage, number of stories, projected floor area, and in the case of demolition work, the General Contractor's permit number, registration number of the demolition industry association, etc. In addition, each one of the four cases requires a separate form for filing a demolition plan. Especially in case 1, the method of demolition, separation of waste material, the amount of expected waste generation (quantities of concrete rubble, asphalt concrete rubble, and construction waste wood), the cost of the demolition work, the name of the recycling plant, and the cost of waste recycling should be described. Furthermore, penalties for violations of the law are provided.

PROGRESS IN RECYCLING AND REUSE OF CONCRETE AS AGGREGATE

Since the early 1970s, a large number of experimental investigations of the quality of recycled aggregate were undertaken [1]. In 1977, the Japan Building Contractors Society (BCS) published the report, "Proposed Standard of Recycled Aggregate and Recycled Concrete and Commentary" [2]. This was the first systematic proposal for recycled concrete in the world. The standard was presented to the European Demolition Association (EDA) during the RILEM International Symposium on Demolition and Recycling of Concrete and Brick Materials, in Rotterdam, Holland, 1985. Some results of the research for the BCS Standard were also presented on the Second RILEM International Symposium on Demolition and Recycling of Concrete and Masonry. Six papers dealing with properties of recycled aggregate, strength, and durability of recycled concrete were presented [3]. The Building Research Institute of the Ministry of Construction of Japan issued the "Proposal of Quality Standard for Recycled Coarse Aggregate" and the "Proposed Standard for Recycled Coarse Aggregate Concrete" in November 1986. In the latter standard, the issue of recycled fine aggregate followed the BCS Standard of 1977.

Table 2 lists the quality standards in terms of water absorption and soundness of the aggregate. In general, it states that recycled aggregate with larger mortar content leads to high water absorption and low quality.

Although some proposals were made subsequently, the Ministry of Construction published the "Tentative Quality Standard Proposal for Concrete" in April 1994. Table 3 lists design strengths for recycled concrete, where the recycled aggregate categories correspond to those of Table 2. Combining high-class coarse and fine aggregate produces Class I recycled concrete, while a combination of low-class aggregate produces low-class

concrete. Table 4 lists examples of types of mainly civil construction and products produced with recycled concrete according to the abovementioned proposals.

METHODS OF MANUFACTURING RECYCLED AGGREGATE

The manufacture of recycled aggregate has many different aspects. These shall be discussed in detail in this section.

Requirements for Original Concrete for Recycled Aggregate

The original concrete to be used for recycled aggregate has to fulfill the following requirements: 1) It shall be free of harmful components such as soil, mud, asphalt, ALC rubble, etc, and 2) it shall be free of harmful substances such as chlorides and alkali-reactive material. In order to guarantee this, an engineer of the concrete debris-processing plant should inspect the demolition site prior to demolition and search for signs of corrosion of reinforcing steel due to chlorides and concrete cracks caused by alkali-aggregate reaction, before accepting the concrete debris as source material for recycled aggregate. It is proposed that a contract between the concrete debris supplier and the processing plant operator be signed after such an inspection.

Recycled Aggregate Manufacturing Process

The general manufacturing process for recycled aggregate is outlined in Fig. 6. After initial crushing, metal chips, impurities and pieces of wood are removed manually on a sieving screen. The material is then crushed again, and metals are removed in two or three stages by a magnetic separator.

Grain Improvement of Recycled Aggregate

Mortar may adhere to the surface of the original aggregate. Its removal will reduce the amount of recycled aggregate with acute angles. Fig. 7 shows the abrading machine, which was developed by the Nuclear Power Engineering Corporation. Crushed coarse aggregate is thrown from the right-hand gate into a circular tube, where it is forced to the left side. After grinding it with a middle cone and the end rotor cone, the mortar is removed from the surface of the original aggregate. Four repetitions of this process produce a good quality aggregate [4].

Fig. 8 shows a machine in which a number of chains are attached to a turning shaft. When the rough crushed concrete rubble is loaded from the top, it is hit repeatedly by the chains and turned into good aggregate [5]. The machine shown in Fig. 9 has an eccentric rotor in a drum and is therefore called eccentric rotor mill. When the roughly crushed aggregate is fed from the top, the inner drum turns and thereby removes the mortar from the recycled coarse aggregate [6]. A plant for processing high-quality recycled aggregate by the eccentric processing machine is shown in Fig. 10. Fig. 11 compares material before and after processing, with almost all adhered mortar removed.

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Removal of Impurities and Low-Density Aggregate by Rising Water Stream

Fig. 12 shows a plant to separate coarse aggregate by density, using a rising stream and vibration. The coarse aggregate is fed into the left side, screened, and while moving to the right side, washed by the rising water stream. Low-density particles float to the top and are discharged into an exhaust ditch. The remaining high-density particles are raked out from the right side [7]. A similar apparatus to separate fine aggregate by density has also been installed, using the same principle, and produces good-quality aggregate.

Removal of Fines by Air Separator

The air separator separates fine powder from fine aggregate. The fine aggregate is fed into the upper part of the equipment, and a centrifugal force and rising air currents remove the fine powder.

Heating and Grinding Method to Manufacture Recycled Aggregate

After preliminary crushing, the original concrete is heated in a shaft furnace up to 300°C for 40 to 60 min, which produces fine cracks between the cement paste and the aggregate (Fig. 13). It is then crushed and the mortar abraded in a tube mill [8]. Good recycled coarse and fine aggregate can be obtained, with small amounts of mortar adhering to the particles and moisture absorption almost as low as that of natural aggregate. Mitsubishi Materials Corp., with financial support from the Ministry of International Trade and Industry (MITI), has built a pilot plant of 300 kg/hr capacity. Fig. 14 compares original concrete rubble with material that was either heated to 300°C or not heated. The composition of the heated recycled concrete is almost the same as the original aggregate, whereas the recycled aggregate that was not heated produced 44% fine powder. Fig. 15 shows a plant of 3 ton/hr capacity. This plant produces about 30 to 40% of the original concrete, with an increased amount of fine powder [8]. The process requires 29 kWh of electric power and 8 kg of kerosene to produce one ton of concrete [9]. At present, the Nuclear Power Engineering Corporation is undertaking a demonstration project to process a huge amount of concrete debris from a demolished nuclear power plant.

TR A0006:2000 – CONCRETE USING RECYCLED AGGREGATE

The technical report “TR A0006 – Concrete using Recycled Aggregate” was issued in November 2000, in the name of the minister of the MITI, assuming that it will become a JIS Specification in the future. The report specifies the minimum quality requirements for recycled aggregate, Table 5. This table also lists the permissible amounts of fines. Since the quality of recycled aggregate fluctuates considerably, quick test methods are required. It is believed that the rate of water absorption of coarse aggregate is an indicator of quality, therefore it is stated that recycled aggregate with a large amount of mortar exhibits a high rate of water absorption, which points to low quality. The test method, described in the appendix of the report, is as follows.

Method to estimate water absorption and loss of soundness of recycled coarse aggregate.

This test method makes use of the close relation between the rate of water absorption and the amount of mortar attached to the original aggregate. After determining the 100 kN crushing value by the BS 812 method, the water absorption Q, in percent, can be estimated by the formula,

$$Q = 0.85 C_g + 1.50$$

where C_g is the 100 kN crushing value, in percent [10]. The loss of soundness, P, of recycled coarse aggregate, also in percent, is then estimated according to,

$$P = 8.0 \times Q$$

Thus, for a Q-value of 5%, the soundness value P becomes 40%. According to Table 2, the durability of second-class and third-class coarse aggregate may be insufficient, but definite conclusions should be drawn only after further evaluation.

Method to estimate water absorption of recycled fine aggregate.

Because of the relationship between water absorption and unit mass of recycled fine aggregate (Fig. 16), the following formula can be used to estimate the water absorption of recycled fine aggregate, Q, [11],

$$Q = -25 T + 41$$

where T is the unit mass of the recycled fine aggregate (kg/l – should be converted to %). This formula requires further examination.

Fines in recycled aggregate.

If the recycled aggregate contains an excessive amount of fines, the amount of required water and shrinkage increase, and the freeze-thaw cycle resistance decreases. The upper limit for fines in recycled coarse aggregate was specified as 2% and for recycled fine aggregate as 10% (see Table 5). If washed with clean water in a machine as shown in Fig. 12, the coarse aggregate can easily meet this requirement, and with the help of an air separator, also fine aggregate can meet this limit.

Salinity of recycled aggregate.

The TR A0006 report cautions against an excessive chloride content in the mortar attached to recycled concrete aggregate. After discussion with the producer, the buyer should specify an upper limit for such chloride content. Unless the recycled aggregate is to be used in unreinforced concrete structures, a visual inspection prior to demolition of the building should be conducted as stated previously, and the specified limit of 0.3 kg/m³ of chloride should be kept.

Alkali-aggregate reaction of recycled aggregate.

If there is the risk of alkali-aggregate reaction with the recycled aggregate, portland blast furnace slag cement Class B can be used. Report TR A0006 specifies that such cement or portland fly ash cement Class B can be used.

PROBLEMS WITH QUALITY OF RECYCLED CONCRETE

The problems with the quality of recycled concrete have already been addressed by numerous papers. The strength of recycled concrete is usually lower than that of normal concrete, for the same water-cement ratio. This fact is particularly noticeable if the original concrete was weak to begin with, because it contained a considerable amount of weak mortar.

Larger shrinkage.

Since recycled concrete contains the mortar of the original concrete and the fines resulting from the crushing operation, the shrinkage of recycled concrete tends to be high.

Low freeze-thaw cycle resistance.

Many reports show that recycled concrete has poor freeze-thaw cycle resistance. Whereas some experiments with air-entrained recycled concrete gave good results, S. Nagataki [12] showed that the freeze-thaw cycle resistance of concrete made with recycled aggregate from non-air-entrained concrete was low. If the original concrete was air-entrained, the results were sufficiently good. It is necessary to confirm these results, because the influence of the amount of fines is significant. According to Report TR A0006, "it is difficult for recycled concrete to have good freeze-thaw cycle resistance. Therefore recycled concrete should be used in underground applications and in regions with mild climate."

Mixed use of recycled and regular aggregate.

When substituting regular aggregate for recycled aggregate, a 30% replacement value results in almost the same strength as achieved with regular aggregate alone, and the effects on the other properties are also small. With 100% recycled coarse and fine aggregate, the strength and durability of the concrete are decreased significantly. Depending on a particular application, there are suitable combinations of recycled and regular aggregate. For example, there is the possibility of combining 100% recycled coarse aggregate with 100% regular sand, or 50% each of recycled and regular coarse and fine aggregate, etc.

USE OF RECYCLED AGGREGATE CONCRETE

Recycled concrete has been studied for more than 30 years, and there exists an extensive literature. However, it was not easy to put the findings to practical use [13]. The



following examples of applications in real structures are particularly noteworthy.

In 1984, the Building Research Institute of the Ministry of Construction built two small test structures using recycled coarse aggregate concrete. Because the recycled aggregate was processed very carefully, no deterioration was observed at all.

In 1995, about 3000 m³ of recycled concrete was placed as the foundation for a temporary structure for the International City Exposition in Tokyo, but the plan was cancelled and the concrete removed. This was very unfortunate for the recycled concrete community.

In 1996, lodgings for members of the House of Counselors were constructed as a demonstration project. 165 m³ of recycled concrete were placed for a 6 cm thick flat slab with an area of 2750 m².

In 1997, two cast-in-place concrete piles with a diameter of 1 m and a length of 30 m were constructed with 100% recycled concrete. Cores with 10 cm diameter were taken from the central part to the full depth of the two piles, and density, compressive strength, etc. were determined. The test results were not bad. At this site, more than 20 piles of the same size were constructed for a five-story building. The building is performing without problems. Since cast-in-place concrete piles are subject to neither drying nor freeze-thaw cycles after construction, they are an application where recycled concrete can be used with advantage [14].

In 1998, the Housing and Urban Development Corporation built an experimental two-story building of 144 m² and a total floor area of 203 m². To date, the building portion built entirely with recycled concrete has shown no abnormal behavior, although net-like cracks were observed. The cracks are still growing gradually, but remain within permissible range. Moreover, the HUDC utilizes concrete debris obtained during the demolition of a housing complex for a rainwater filtration system, a container for crushed aggregate storage, a small retaining wall, as prepacked material for a pavement, and as a soil and ground improvement material.

In 2000, a single-story pump room with an area of 127 m² for a water tank was built using recycled aggregate that was produced by the heating and abrasion method. The recycled concrete can be used in the same way as normal aggregate concrete.

Recycled concrete is also being used as a porous material for plant beds. Some companies have launched trial production of road curbstones and other simple concrete products like blocks and others for which there is a public demand. However, the public demand was very low.

In Japan, there are only three or four ready-mix recycled concrete plants. Their output is used mainly as foundation for wooden houses and exterior concrete, etc. Fig. 17 shows

the volume of ready-mix recycled concrete delivered by the Tateishi plant. About 40,000 m³ of recycled concrete is produced each year. Therefore, about 120,000 m³ of such concrete is produced altogether in Japan each year.

In recent years, test results for bending, shear and bond strength of small recycled concrete beams were reported. According to these reports, their mechanical properties are not much different from those of normal aggregate concrete beams.

RECYCLING OF CONCRETE RUBBLE FOR ROADBASE AND BACKFILL

As shown in Table 1, 35 million tons of concrete rubble were generated in fiscal year 2000. The recycling rate was 96%. At the demolition site, the concrete rubble is crushed by mobile crushing equipment and then used on site as road base material, for land reclamation, backfill, etc. The remaining concrete rubble is sent to a processing facility, where the majority of the material is crushed to minus 40 mm size. Table 6 lists the main uses of concrete rubble according to the "Recycling Law". The main uses today are as crushed stone layer and recycled fine aggregate. In 1992, the Japan Road Association issued a "Technical Guideline for Recycled Pavement Construction" for the use of concrete rubble as road base material.

USE OF CONCRETE POWDER, ECO-CONCRETE AND SLURRY

Use of Concrete Powder.

When crushing concrete rubble to produce recycled aggregate, a large volume of fines is generated, which contains considerable amounts of cement hydration products. Many experiments have been carried out to determine whether this powder can be used as cement replacement, but it was found not to contribute to strength development.

In 1976, the author has tested a powder made entirely from concrete rubble. The molar ratio was adjusted by adding lime. After mixing the powder with water, it was subjected to autoclave curing, immediately after which strengths of 30 – 40 N/mm² were obtained. The strengths changed as the concrete mixes were varied and different original concrete rubble was used. The reason was probably due to the mineral composition of the aggregate for the original concrete, which depends on the place of production [15].

In another test, the fine powder collected by the air separator was heated up to 600°C and ground to an even finer powder in a mill. It was possible to replace about 10% of the cement [16]. The fine powder can be added as a filler to highly flowable concrete or to control segregation. However, as more water is added, the strength decreases and shrinkage increases.

Mixed with mud and chemical admixtures, the fine powder is being studied as a material to fluidize soils. If the powder is produced near a cement plant, it can be readily used as a raw material for cement production. But this has not yet been put to practice.

Recycling of limestone aggregate concrete (Eco-Concrete).

According to Tomosawa et al. [17], concrete rubble can serve as raw material for cement production, if limestone aggregate was used in the original concrete. This material has been named “Eco-Concrete” and is currently undergoing detailed study. However, if the use of limestone aggregate is as widespread as in Japan, it will be depleted within 40-50 years, and no cement plants will be operational when Eco-Concrete structures are demolished, because the service life of reinforced concrete structures is 60 years or longer. Therefore, it may be said that Eco-Concrete is not reusable after all. The use of limestone aggregate cannot be recommended. On the contrary, it should be reserved for more important applications such as for cement manufacture, steel production, and as raw material for many chemicals.

Reuse of concrete slurry.

Research on the reuse of washing water from ready-mix plants, from returned concrete, and sludge removed from concrete has started in Japan in the 1970s. The JCI has compiled a report in 1975. The treated water can be used as mixing water for concrete. Furthermore, the JCI committee determined that up to 3% sludge (converted to dry equivalent) can be used for new concrete (not as cement replacement). This recommendation was accepted in JIS A-5308 [18].

Since civil engineers have been concerned in recent years about the durability of concrete, the idea of mixing sludge with new concrete is not very popular. But the disposal of sludge has become a major problem. It can be processed into a cake, and if a cement plant is nearby, used as a raw material for cement production. After drying and heating, and mixing it with ground granulated blast furnace slag, it can be turned into a blended cement. Although such a material has been produced temporarily, it is not being manufactured at present.

CLOSING WORDS

This paper dealt with recent trends in industrial waste processing, recycling of concrete rubble and related waste materials in Japan. The main points made were as follows.

1. The amounts of construction waste and recycling as a resource were mentioned. More than 95% of concrete rubble are being recycled and used mainly as road base material.
2. Landfill sites suitable for industrial waste are becoming scarce. Their combined capacities will last for only another 2 to 3 years.
3. The Ministry of Land Infrastructure and Transportation has enacted a “Construction Recycling Law” in May, 2002, to enforce the recycling of construction waste.
4. Methods of producing recycled aggregate were discussed, and new technologies to produce high-quality aggregate were introduced.

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5. An outline of Technical Report TR A-0006 (Recycled Aggregate Concrete) was given.
6. The trends of recycled concrete usage from 1984 to date were outlined, which at present results in about 120,000 m³ of concrete being produced annually.
7. Problems associated with “Eco-Concrete”, fine concrete powder, and concrete slurries were mentioned.

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Table 1. Amounts of Construction Byproducts

Fiscal Year	1990		1995		2000	
Items	Generated ($\times 10^6$ tons)	Recycled (%)	Generated ($\times 10^6$ tons)	Recycled (%)	Generated ($\times 10^6$ tons)	Recycled (%)
Concrete Rubble	25.4	48	36.0	65	35.0	96
Asphalt Concrete	17.6	48	36.0	81	30.0	98
Construction Waste Wood	7.5	31	6.0	40	5.0	38
Construction Waste Mud	14.0	8	10.0	14	8.0	41
Mixture of Construction Waste	1.5	14	10.0	11	5.0	9
Other Waste	1.5	40	1.0	–	2.0	–
Total	75.9	–	99.0	58	85.0	85

Table 2. Quality of Recycled Concrete Aggregate

	Recycled Coarse Aggregate			Recycled Fine Aggregate		
	1 st Class	2 nd Class	3 rd Class	1 st Class	2 nd Class	
Water Absorption (%)	<3	<3	<5	<7	<5	<10
Loss of Soundness	<12	<40*	<12	-	<10	-

* In this case, do not consider freeze-thaw deterioration

Table 3. Design Strength of Recycled Concrete

Class of Recycled Concrete	Coarse Aggregate	Fine Aggregate	Design Strength (MPa)
I	Recycled coarse aggregate 1 st class	Ordinary aggregate	>20 (RC)
II	Recycled coarse aggregate 2 nd class	Ordinary aggregate or Recycled aggregate	>16 (Plain)
III	Recycled coarse aggregate 3 rd class	Recycled aggregate	<16

**Table 4. Examples of Structures Using Recycled Concrete
(Civil Construction, not Buildings)**

Class of Recycled Concrete	Usage	Coarse Aggregate	Fine Aggregate	Structures
I	RC & Plain C	Recycled coarse aggregate I class	Ordinary aggregate	Bridge substructure, retaining wall, tunnel liner
II	Plain C	Recycled coarse aggregate II class	Ordinary or recycled fine aggregate 1 st class	Concrete block, foundation of road attachment, side drain, foundation of water catchment box, fill concrete, side slope frame, gravity bridge basement, wave breaker, erosion control dam
III	Concrete sub slab	Recycled coarse aggregate III class	Recycled fine aggregate 2 nd class	Concrete sub slab, concrete screed, back fill concrete, non-structural members

Table 5. Quality of Recycled Concrete Aggregate (After TR A 0006)

	Recycled coarse aggregate	Recycled fine aggregate
Water Absorption (%)	<7	<10
Amount of Fineness (%)	<2*	<10*

* When the manufacturing method is wet process, this value will be satisfied, so the test is not needed. For dry process, this value is sometimes not satisfied, so it should be confirmed by wet test.

Table 6. Main Usage of Concrete Rubble in “Recycling Law”

Category	Main Usage
Crusher Run	Load subbase material, back fill and base material for public construction, basement material for building
Recycled Fine Aggregate	Filling and basement material for construction
Recycled Size Controlled Crushed Aggregate	Other upper layer roadbed material
Recycled Cement Stabilized Roadbed Material	Roadbed material for road pavement and other pavement
Recycled Lime Stabilized Roadbed Material	Roadbed material for road pavement and other pavement

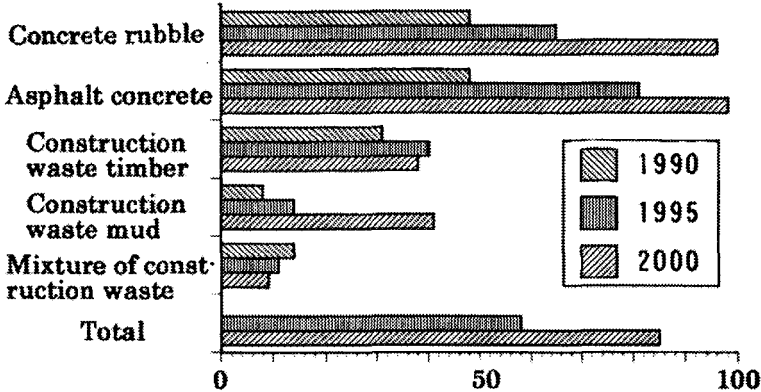


Fig 1: Recycling rate of construction wastes

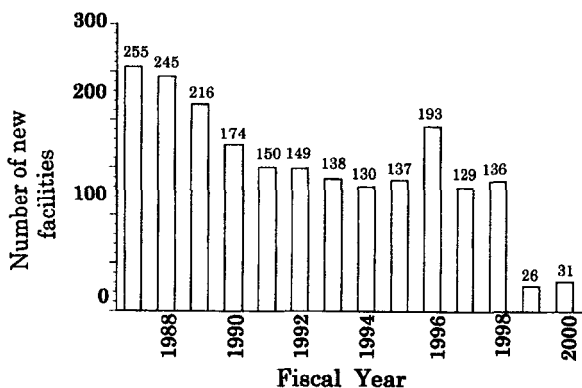


Fig 2: Number of new facilities for industrial wastes

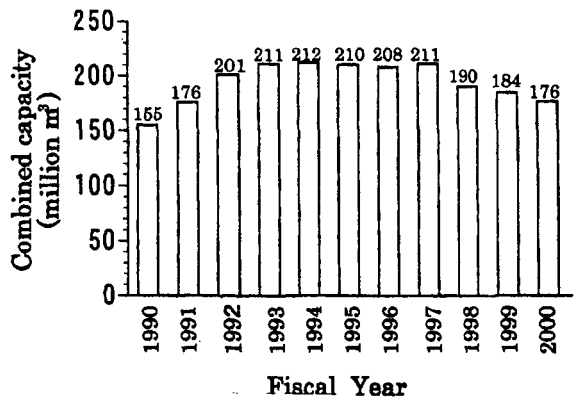


Fig 3: Remaining capacity of safe landfills for industrial waste

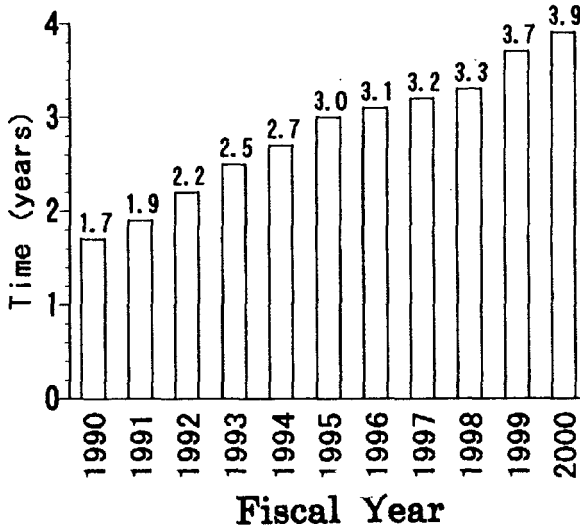


Fig 4: Remaining life of safe landfills for industrial waste

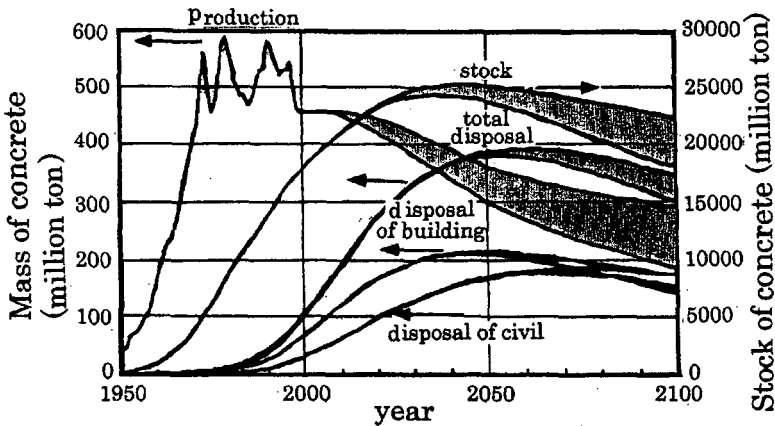


Fig 5: Mass of production, disposal and stock of concrete in the future

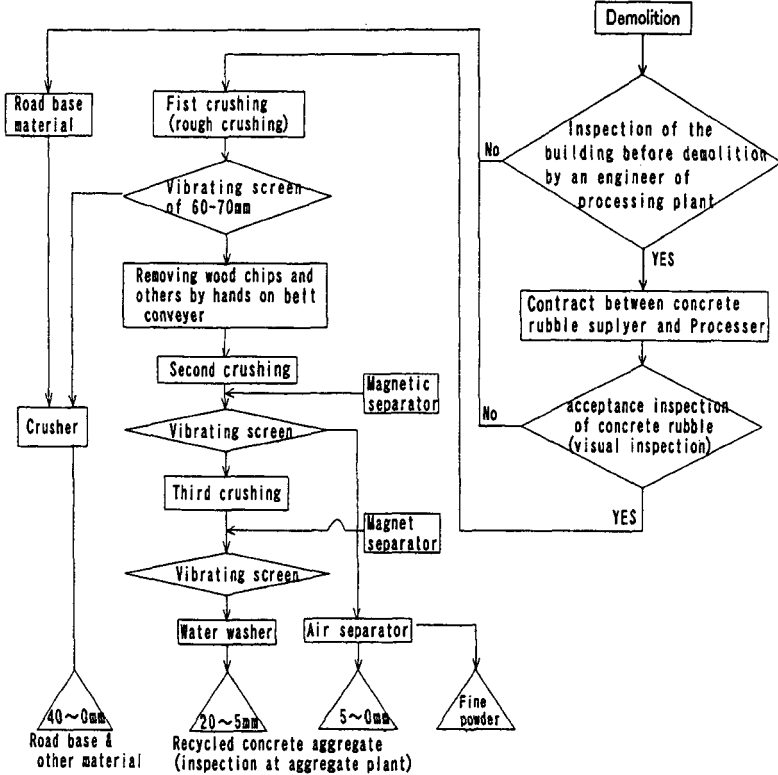


Fig 6: Outline of manufacturing process of recycled aggregate

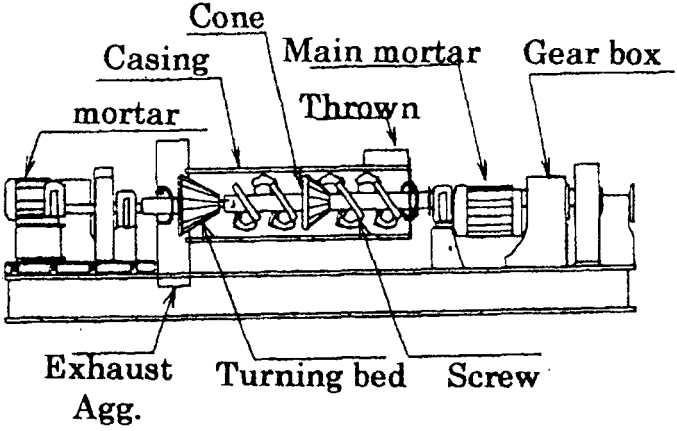


Fig 7: NPEC rubbing method

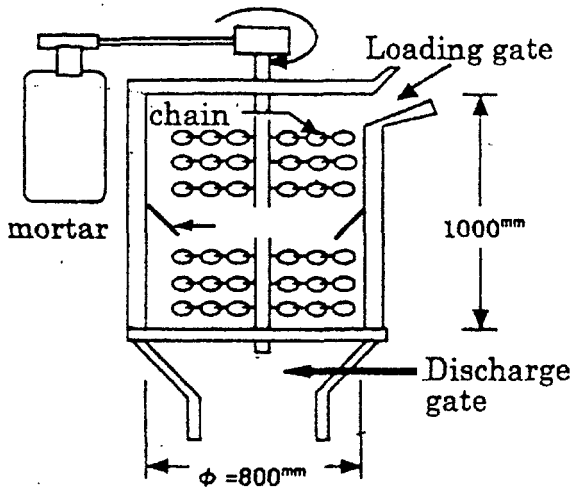


Fig 8: Schematic figure of chain Rotor machine

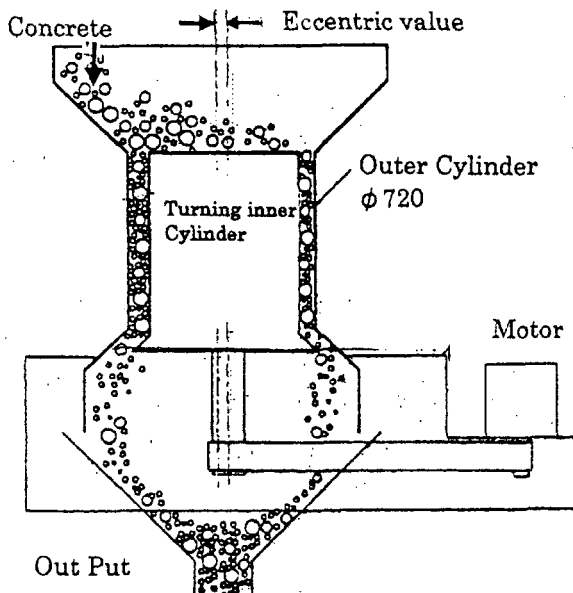


Fig 9: Outline of eccentric rotor processing machine

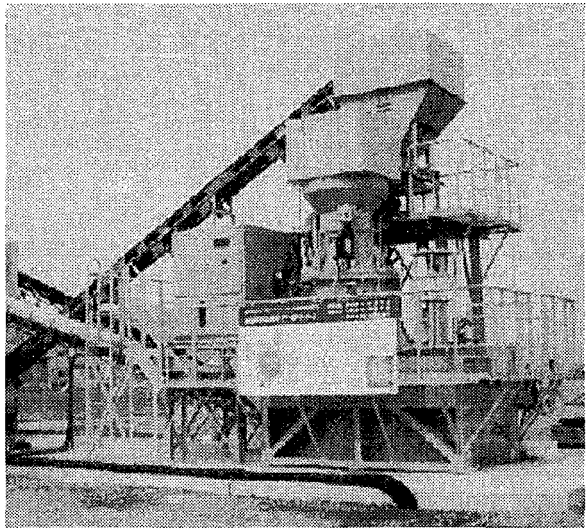


Fig 10: High quality recycled aggregate processing

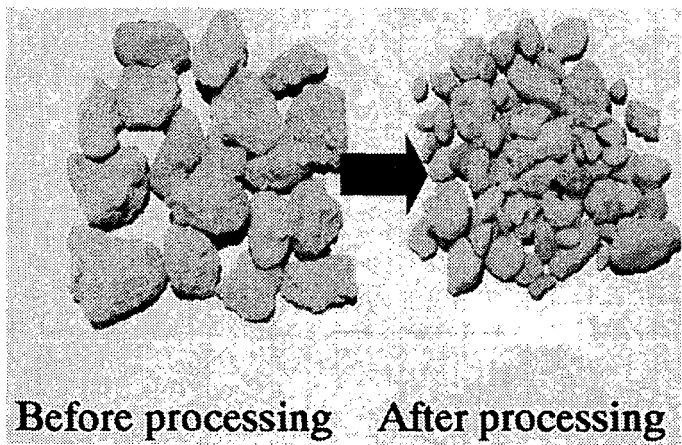


Fig 11: Comparison of processing
Before and after

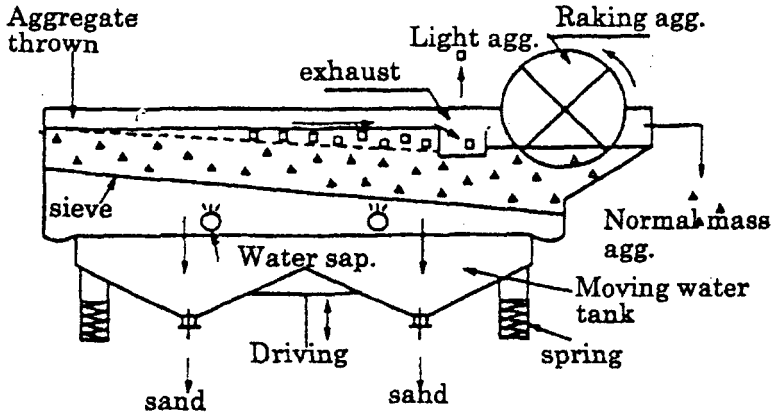


Fig 12: Removal of impurities and low density aggregate by rising water stream machine

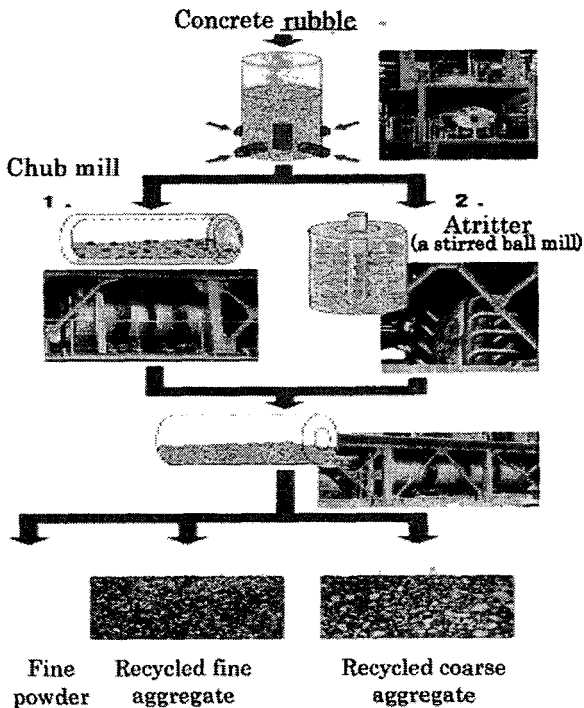


Fig 13: Process of heating and abrading method

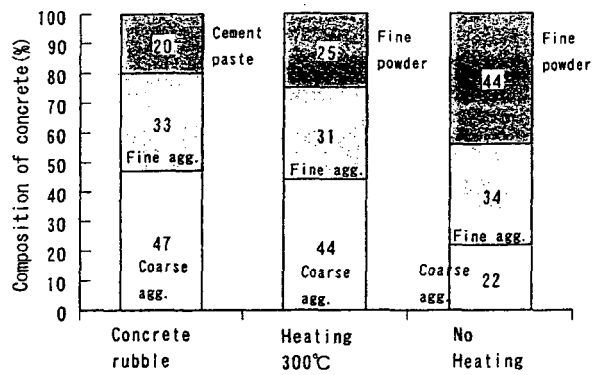
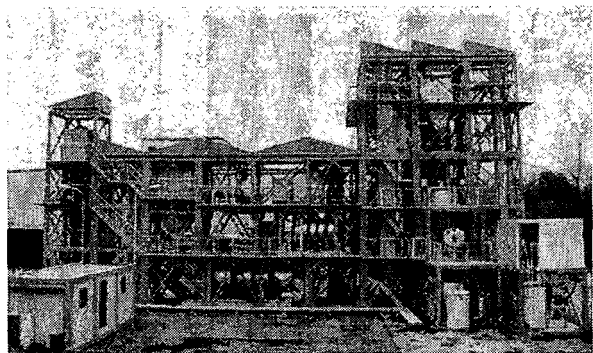


Fig 14: Composition of original concrete and recycled concrete



Outline of heating and abrading plant 3 t/h capacity

Fig 15: View of heating and abrading plant

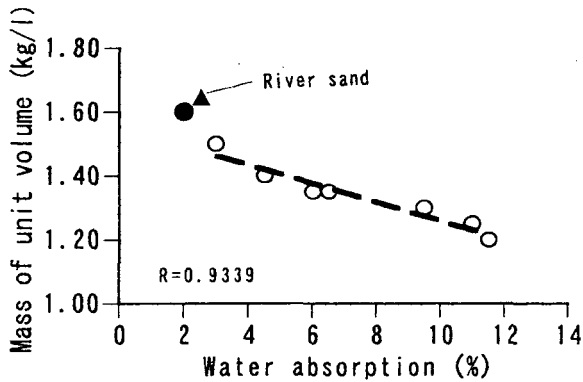
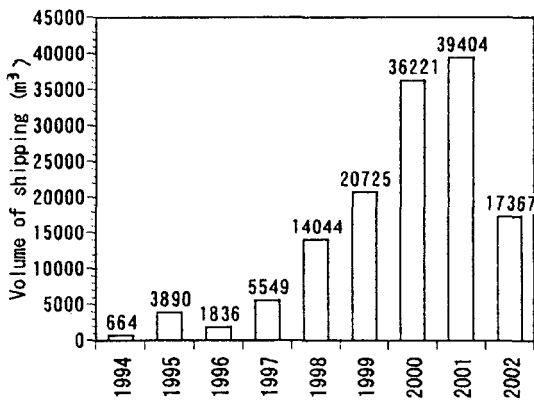


Fig 16: Relation between water absorption of recycled fine aggregate and mass unit volume



(Till July)

Fig 17: Volume of shipping of recycled ready mixed Concrete in a year

Concrete Waste in a Global Perspective

by T. C. Hansen and E. K. Lauritzen

Synopsis: The reduction and utilization of waste and by-products is one of many challenges facing mankind in the modern world. This paper consists of an overview of the handling of the world's concrete waste and is concerned with unbound applications of blended construction and demolition (C&D) rubble for pavement bases and sub-bases in road construction. The problems of recycling mixed wastes are considered and global perspectives are presented on the use of C&D rubble. The paper proposes that studies should be carried out in order to research the technical properties of blended C&D rubble, which the authors believe would be economically and environmentally justifiable in promoting the widest possible range of recycled products for road construction.

Keywords: asphalt; bases; bricks; concrete; construction and demolition waste; demolition; recycling; road construction; sub-bases

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INTRODUCTION

Almost all forms of human activity create one or more types of waste, which can often be recycled. This is also true of construction and demolition (C&D) waste.

After a period of time buildings are no longer suited to their original purpose and in many parts of the world natural catastrophes and wars also contribute significantly to the destruction of buildings and structures.

The reduction and utilization of waste and by-products is one of many challenges facing mankind in the modern world.

Reduction of waste in order to protect nature against pollution and in order to meet the increasing shortage of suitable dumping grounds. Utilization of waste by recycling in order to save energy and natural resources.

CONSTRUCTION AND DEMOLITION WASTE AND RUBBLE

Municipal waste consists of domestic waste, commercial waste, industrial solid waste and C&D waste.

C&D waste derives from new building and construction work and from renovation and demolition of buildings and structures. C&D waste includes among other materials concrete, asphalt and masonry, natural stone, wood, paper, plastics, cardboard, glass, metals and problem wastes. Soil is not considered a waste material, and most metals are recovered before they enter the waste stream.

C&D rubble consists primarily of broken concrete, asphalt and bricks, either in the form of separate fractions or mixed.

Close to 50 % of all municipal solid waste is C&D waste, and most of it is concrete, asphalt and masonry rubble. So in principle it should be possible to reduce by up to one half the total amount of municipal solid waste which is generated within any large city in

the world by separating, processing and recycling C&D rubble apart from the main municipal solid waste stream.

In most parts of the world municipal solid waste is currently dumped at common landfills. A minor part is incinerated. Such disposal is undesirable and it is increasingly being discouraged by law and by high landfill disposal fees. This is why it would have far-reaching implications if the amounts of municipal waste could be substantially reduced by recycling C&D rubble. That is currently being done in Copenhagen, the capital of Denmark, a city of 1.5 million people (1).

RECYCLING CLEAN FRACTIONS OF C&D WASTE

It is the aim of any recycling effort to reuse waste products for the highest possible value.

Ideally old concrete should be reused as aggregate for production of new concrete. Old asphalt should be reused in new asphalt pavements, and old bricks and roofing tiles should be cleaned and reused for their original purpose.

In actual practice much old clean concrete of high quality from highway pavements and other major civil engineering structures is crushed, screened and reused as aggregate for concrete in new construction works. This has been done by the U.S. Army Corps of Engineers and numerous State Highway departments in the U.S. for at least 30 years¹ (1)(2). In order to facilitate such reuse ASTM C-33, Standard Specifications for Concrete Aggregates, allows the use of clean crushed hydraulic cement concrete as coarse aggregates on a par with natural materials (2).

Much old clean asphalt is also recycled in normal asphalt production as a matter of routine. Old bricks and roofing tiles are rarely used for their original purpose except in restoration work or for decoration.

RECYCLING MIXED C&D RUBBLE

It is the recycling of mixed C&D rubble that gives rise to problems. Whole bricks and roofing tiles are rarely reused for their original purpose, because it is difficult and costly to remove old cement mortar from masonry and to grade the bricks. About 50 % of all old asphalt remains as waste, which for practical reasons cannot be reused in conventional asphalt surfaces. Old concrete from demolished buildings and structures is often of so questionable a purity and quality that it is unsuitable as aggregate in the production of new concrete. These are the reasons why huge quantities of old concrete, asphalt and masonry enter the municipal solid waste stream, most of it in the form of mixed rubble.

¹ Rilem Report 6, Recycling of Demolished Concrete and Masonry, pp. 111-112, on recycling of pavement in USA

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Practical and economic considerations suggest that optimum value reuse of concrete, asphalt and brick rubble is achieved when the rubble is crushed and used as road base or sub-base materials (1).

If all the C&D rubble generated within an average city were to be processed and used for road construction and maintenance purposes, processed C&D rubble could substitute 20 % of the consumption of natural sand, gravel and crushed stone in the city (1). For that reason it is evident that there is a potential market for processed C&D rubble provided the recycled materials can be made available at the right price and quality. As an added advantage to recycling its C&D rubble a city may be spared millions of tonnes/km of transportation of materials through the application of proper logistics (1).

PREREQUISITES FOR THE SUCCESSFUL RECYCLING OF C&D RUBBLE

Systematic recycling of C&D rubble is seldom the outcome of spontaneous development. Initially it requires the introduction of a reliable registration and collection system for C&D wastes. New laws and regulations must also be introduced and enforced.

However, first and foremost three practical requirements must be satisfied before any recycling scheme can be brought to function:

1. Selective demolition must be made mandatory.
2. Processing plants and depots for recycled materials must be established.
3. Recycled products must be produced and marketed to compete with comparable new raw materials in terms of price and quality.

Re 1. In order to achieve an acceptable economy for any recycling scheme for C&D waste, selective demolition and sorting of waste at source must be made mandatory. Selective demolition is defined as a process in which demolition takes place as 'reverse construction'. Different-types and fractions of materials are removed from condemned structures and sorted at the demolition sites, so that mixing of wastes is avoided. Selective demolition and sorting of waste is now required at all major demolition sites in Copenhagen. In the process serious attempts are made to separate, store and transport concrete, asphalt and masonry rubble in three clean fractions, but this is not always possible. Mixed C&D rubble remains a problem.

Re 2. It is necessary to establish processing plants and depots at strategic locations within a city in order to achieve the flexibility and economy necessary for employing recycled materials. The right materials must be available in the right quantities, at the right place, at the right price and at the right time. These conditions are met by a single, large and conveniently located C&D waste recycling facility in Copenhagen (1).

Re 3. Most recycling efforts depend on subsidies in order to achieve a balanced economy. This is also true for what concerns recycling of C&D waste. The cost of

selecting, sorting and processing of waste is usually higher than the value of comparable new raw materials. However, recycling of C&D waste can be made economical by imposing a fee on C&D waste, which is dumped at landfills or incinerated. The disposal fee is waived when sorted C&D waste is brought to recycling plants. From there on market economy takes over. As disposal fees gradually continue to climb, which is in the nature of all taxes and fees, a level is soon reached where commercial recycling of C&D rubble more than pays for itself (1).

Regarding product quality it is a prerequisite that recycled materials either satisfy the requirements of already existing specifications for primary raw materials or that special norms and standards be developed for recycled materials.

Danish specifications have been issued for the use of clean crushed asphalt and brick rubble as unbound road base materials (3)(4), and specifications for the use of crushed concrete are being developed. So the user is guided by official documents when he applies clean fractions of rubble, which are represented by the three corners of the ternary diagram, ABC, in Figure 1.

BLENDED ROAD BASE MATERIALS

In spite of all good intentions associated with selective demolition it has proved difficult and expensive to keep concrete, asphalt and masonry rubble separate in clean fractions on busy demolition sites. More often than not, asphalt and masonry rubble are mixed with concrete when received at recycling plants, and once the materials are mixed, they are impossible to separate again.

As a consequence of such practical difficulties the Copenhagen Recycling Centre launched two new blended products for road base construction purposes.

One is a blend of nominally 50 % crushed clean concrete and 50 % crushed asphalt. The other is a blend of nominally 55 % crushed bricks and 45 % crushed concrete. Points D and E in Figure 1 represent the two blends.

Blends of bricks and concrete are covered by Danish specifications (3), but blends of asphalt and concrete are not currently covered.

For a number of reasons the blended materials have quickly become popular among contractors. They now make up more than 90 % of all sales of recycled products from the Copenhagen Recycling Centre and there have been no complaints. This indicates a high level of customer satisfaction.

In the case of blends of crushed concrete and crushed asphalt, lubricating properties of the bitumen reduce the effort required to compact the material by rolling, and under traffic loads the mixed granular material is stronger than crushed concrete, probably due to a cohesive effect of the bitumen. Moreover, the blend supports prolonged static loads better than pure asphalt because of a proportionally lower content of bitumen. Evidently

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blended crushed asphalt and concrete performs better than pure crushed asphalt or pure crushed concrete. This is interesting considering that Danish specifications allow the use of pure crushed asphalt as base material for heavily trafficked roads.

Pure crushed bricks and tiles have never been popular in Denmark as road construction materials. But blends of crushed bricks and crushed concrete were well received by customers as base materials for lightly trafficked roads. The blend has good strength, it can be used under very wet conditions and it offers good support for provisional access roads. Evidently, a blend of crushed bricks and concrete has technical advantages over pure crushed bricks.

From this point of view it does not seem logical to specify the use of pure fractions of crushed concrete, asphalt or bricks, and to pay extra costs associated with the sorting, processing and storage of separate pure fractions, where mixed rubble will serve the purpose equally well or better.

As a quality measure of road base materials, "relative customer satisfaction" has been selected as an all-embracing technical and economic index of product quality.

Figure 2 is a three-dimensional perspective representation of the ternary diagram in Figure 1. On the basis of practical user experience, relative customer satisfaction is plotted along the ordinates in Figure 2 at points A, B, C, D and E. In that way points A', B', C', D' and E' are obtained. By connecting the five points by straight lines a surface emerges in space, shown hatched in Figure 2. It is suggested that this surface, based on our current knowledge, is the best estimate of the quality of the entire spectrum of blended road base materials which can be produced from crushed concrete, asphalt and bricks.

It will be seen from Figure 2 that all blended materials perform better than pure crushed bricks, which constitute the lowest quality product in our spectrum. It also appears that many binary and ternary blends can be expected to perform better than pure fractions of crushed concrete or crushed asphalt. This is not surprising. It is well known that the blending of two or more components often provides composite materials with better properties than either of the components. This is true for blends of natural sand and gravel, so why not for granular wastes? The presence of bitumen, even in small quantities, appears to impart new and useful properties to blends of mineral particles. It apparently changes the properties of the blends from predominantly brittle to more ductile.

If one is prepared to accept the fact that some blends of crushed concrete, asphalt and bricks perform better than pure materials, then it suggests itself to undertake systematic studies of key technical properties of blended C&D rubble pertaining to road construction.

Properties such as compactability, bearing capacity, durability and environmental acceptability should be studied as functions of mix proportions of crushed concrete, crushed asphalt and crushed bricks.

Experimental data should be obtained in order to determine the widest possible limits within which mixes of crushed C&D rubble can be used as road construction materials in different climates and under different traffic conditions. The data should allow specifications to be prepared which will permit and promote use of blended or mixed C&D rubble for road construction purposes.

The incentive to carry out the study is considerable, because mixed rubble is simpler to handle and it is less expensive to produce than pure waste fractions.

Finally we refer to a study of the recycling of airport structures at Fornebu old airport, Oslo (5), which has demonstrated very positive results on the recycling of blended materials.

GLOBAL PERSPECTIVES OF USING MIXED C&D RUBBLE AS ROAD CONSTRUCTION MATERIALS

It is evident that large environmental and economic benefits would be associated with simple and cost-efficient handling and use of C&D rubble in quantities which may well amount to one half of all the world's municipal solid waste.

The authors have analysed the prospects of systematic recycling of C&D rubble in various cities around the world. The results are presented in Table 1. In order of importance, the three main factors affecting the prospects of recycling of C&D waste are population size and density, occurrence of, and access to natural raw materials, and level of industrialization. This is highlighted below by three examples drawn from Table 1. Other important but less predictable factors affecting the prospects of recycling of C&D rubble are wars and natural disasters such as earthquakes, hurricanes and floods.

Amsterdam in the Netherlands is the first example. The city is densely populated. Natural raw materials are scarce and the level of industrialization is high. It is not surprising that the highest possible value recycling of C&D waste is practised in the Netherlands.

Copenhagen in Denmark is our second example. The city is densely populated and the level of industrialization is high. However, because there is an ample supply of natural raw materials, economics and common sense dictate lower value recycling than in Amsterdam. Production of pure fractions of C&D rubble has proved uneconomical and the commercial market has shown a preference for blended rubble. This is in spite of the fact that public authorities for environmental reasons have discouraged the use of mixed materials.

Dacca in Bangladesh is the third example. The city is densely populated. Access to natural raw materials is difficult, and like other Third World cities Dacca struggles with

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the problem of reducing huge quantities of municipal solid waste that daily adds to already immense and unsanitary landfills. It would appear that the use of C&D rubble as road construction materials could substantially assist in solving both a waste disposal problem and a raw materials supply problem. This is true also for other large cities in the Third World that, contrary to Dacca, are located close to abundant raw materials deposits, but where permanently congested traffic conditions make access to the deposits difficult. Mexico City is an example in point.

However, selective demolition and sorting of waste on site cannot be made as effective in emerging as in developed nations. Mixed rubble of highly variable quality will have to be accepted if the idea is going to be useful. Practical experiences from Denmark indicate that crushed concrete rubble can be successfully used for road construction purposes even if neither the sorting out of soil, wood and plastics from the rubble nor the crushing of the rubble is strictly controlled during production of the recycled granular material. It is expected that results of the suggested systematic study of the properties of mixed C&D rubble will confirm this conclusion. What will be needed then is the preparation of more practical basic documents for simple road construction in emerging nations, including less complex code requirements, which will facilitate and promote the use of recycled waste materials.

A special Danish recycling effort has been directed towards international disaster relief and assistance in demolition of damaged buildings and recycling of building materials after catastrophes of nature and wars. Examples described in [1] are the reconstruction of war-damaged areas in Beirut in Lebanon and Mortar in Bosnia.

SUMMARY AND CONCLUSIONS

Municipal solid waste consists of domestic waste, commercial solid waste, industrial solid waste and construction and demolition waste (6).

C&D waste derives from new building and construction work and from renovation and demolition of buildings and structures. C&D rubble consists primarily of broken concrete, asphalt and bricks.

Close to 50 % of all municipal solid waste is C&D waste, and most C&D waste consists of rubble, much of it is demolished concrete. So in principle it should be possible to reduce by up to one half the total amount of municipal solid waste, which is generated within an average city by separating, processing and recycling C&D rubble apart from the main municipal solid waste stream.

In most parts of the world municipal solid waste is currently dumped at common landfills. A minor part is incinerated. Such disposal is undesirable and it is increasingly being discouraged by law and by high landfill disposal fees. This is why it has far-reaching implications if the overall quantities of municipal waste can be substantially reduced by recycling of C&D rubble. That is currently being done in Copenhagen, the capital of Denmark, a city of 1.5 million people.