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Recycling of Demolished Concrete

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Synopsis: In Japan, it has been predicted that enormous quantities of demolished concrete will be produced in the future. Therefore, a great deal of research is being conducted to find ways to recycle this demolished concrete as concrete aggregate. However, because the characteristics of the original concrete are not well known in many cases, the results are also not clear. Moreover, the recycling of the cement in concrete is also necessary from the standpoint of resolving global environmental problems and achieving sustainable development. This paper describes the properties of the concrete made with recycled aggregates from the original concrete of known quality and the recycling of the cement in concrete as the approach that should be taken in the 21st century.

Keywords: aggregate; carbon dioxide emissions; cement; concrete; recycling

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INTRODUCTION

The concept of sustainable development has been proposed for what has been called our "finite deteriorating planet". This concept involves reducing the environmental burden to the greatest extent possible and building a society based on recycling.

In the concrete industry as well, recycling is currently being studied for demolished concrete. This material is already being reused as road base course and foundation material. In the future, however, this demolished concrete must be recycled as concrete aggregate, and recycling must also be extended to include the cement in the concrete as well.

CONCRETE RECYCLING IN JAPAN

According to the Ministry of Welfare, 400 million tons of industrial wastes are produced in Japan each year (Fig. 1). The construction industry is a major source of these wastes. The industries are currently promoting waste reduction and recycling, and so the quantity of final disposal wastes now represents about 17% of the total. However, the capacity of final disposal sites is currently limited to only three years.

A survey conducted by the Ministry of Construction in 1995 found that the total quantity of construction wastes produced each year came to nearly 100 million tons, and demolished concrete was the leading component of these wastes. accounting for 37 million tons (Fig. 2). While 65% of concrete wastes are recycled, they are reused mainly as road base course and foundation material, and almost none is recycled back into concrete.

Almost all of the concrete structures in Japan have been built over the last 50 years. As a result, the quantity of demolished and discarded concrete is expected to increase dramatically in the coming years (Fig. 3) (1). For this reason, there are many ongoing researches aiming to recycle waste concrete as concrete aggregate. However, in many cases the characteristics of the original concrete are not well known, so that the properties of the concrete made with recycled aggregates are not predictable.

Furthermore, even recycling of demolished concrete as concrete aggregate becomes possible, it would not be adequate for a closed recycling system to turn old concrete back into new concrete. Accordingly, special types of fully recyclable concrete that use limestone aggregate (2) and recycling of the cement in demolished concrete as well (3) have been proposed.

The objectives of the study are to clear the properties of recycled aggregate concrete and to propose new recycling system that covers cement as well.

RECYCLED CONCRETE AS AGGREGATE

Original Concrete

The original concrete prepared for this investigation contained normal portland cement, river sand, crushed stone and an air-entraining and water-reducing admixture. The properties of the original aggregates are shown in Table 1. Original concrete cubes for producing recycled aggregate, 300 mm by 300 mm by 300 mm in size, were made with three mixture proportions representing high, moderate, and low strength as shown in Table 2. After water curing, the original concrete cubes were demolded at the age of 28 days and exposed outdoors. They were processed into recycled aggregate at the ages of 1 month, 1 year, and 2 years.

At the same time, cylindrical specimens 100 mm in diameter and 200 mm in length were fabricated. The properties of the original concretes are shown in Table 3. The compressive strength of concrete specimen at 28 days under standard curing conditions were 60.7 MPa for HSC, 49.0 MPa for MSC, and 28.3 MPa for LSC, respectively.

Production of Recycled Aggregate

The crushing was carried out in accordance with the flow chart shown in Fig.4. The original concrete underwent primary crushing with a jaw crusher and secondary crushing with an impact crusher. This stage is referred to as crushing level 1. Further crushing stages using an improved jaw crusher with a strong grinding effect once and twice are referred to as crushing level 2 and crushing level 3, respectively. The recovery ratios of coarse aggregate for crushing level 1, 2, and 3 were 60%, 45%, and 30%, respectively, with the mass of the original concrete being 100%, in which the mass ratio of original coarse aggregate was approximately 43%. The strength of the original concrete had no appreciable effects on these recovery ratios. The properties of the recycled coarse aggregates produced are given in Table 5. Generally speaking, using higher strength concrete and a higher crushing level can produce recycled coarse aggregate of better quality. However, the aggregates did not satisfy the Japanese Industrial Standard (4) for concrete aggregate in terms of density and water absorption.

Strength Characteristics

The materials used with recycled coarse aggregate comprised normal portland cement, river sand, and an air-entraining and water-reducing admixture. The river sand was the same as used in the original concrete. The mixture proportions are given in Table 4. When the water-binder ratio was 0.35 or less, silica fume and an air-entraining and high-range water-reducing admixture were used.

Fig. 5 shows the relationship between the binder-water ratio and the 28-day compressive strength of recycled concrete using aggregates reclaimed at 1 month with 3 levels of crushing. The compressive strength of concrete containing recycled coarse aggregate depends on the compressive strength of the original concrete. The compressive strength of recycled aggregate concrete was similar to original aggregate concrete and retained a linear relationship with the binder-water ratio of up to 1.5 times the 28-day strength of the original concrete. The level of crushing had no appreciable effect on the compressive strength.

Fig. 6 shows the relationship between the binder-water ratio and the 28-day compressive strength of recycled concrete using aggregates reclaimed at 1 month, 1year, and 2 years with crushing level 2. The age of concrete at the time of crushing (crushing age) had no appreciable influence on the compressive strength of recycled concrete using aggregate made from the original concrete with high strength (HSC) and moderate strength (MSC). For the original concrete with low strength (LSC), the compressive strength of recycled concrete was somewhat influenced by crushing age. The concrete made with the recycled aggregate reclaimed at 1 year or 2 years exhibited higher compressive strength in comparison to the recycled aggregate reclaimed at 1 month.

Resistance to Freezing and Thawing

The materials used were the same as those used in the test of concrete strength. The mixtures were proportioned to provide a slump of 8 ± 2.5cm and air content of 4.5 ± 1.5%, with the water-cement ratio being constant at 0.55. The freezing and thawing test procedure was in accordance with ASTM C 666 Procedure A, though the test was initiated at an age of 28 days.

Fig. 7 shows the changes in the relative dynamic modulus with freezing and thawing cycles for the recycled concrete using aggregates reclaimed at 1 month with 3 levels of crushing. Recycled aggregate concrete showed larger losses in the relative dynamic modulus than the original aggregate concrete. The losses were larger for aggregates made from low and moderate strength concrete. Large losses were also found in the case where the crushing level was low. Though the resistance to freezing and thawing decreased, the durability factor was greater than 70 at 300 cycles, which is generally considered as satisfactory.

Fig. 8 shows the changes in the relative dynamic modulus with freezing and thawing cycles for the recycled concrete using aggregates reclaimed at 1 month and 1 year with crushing level 1. At crushing age of 1 year, the resistance to freezing and thawing of recycled aggregate concrete was improved and similar to original aggregate concrete.

Fig. 9 shows the relationship between the mass losses by the soundness test (5) on coarse aggregate and the durability factor of the concrete using these aggregates at 300 cycles. For crushing age of 1 month, the mass losses correlated relatively well with the durability factor. Though the threshold value for mass losses is generally assumed to be 12%, a mass loss of as high as 60% of recycled coarse aggregate provided sufficient resistance to freezing and thawing for the concrete. For crushing age of 1 year, the durability factor was retained over 90 regardless of the soundness of recycled coarse aggregate.

Fig. 10 shows the changes in the relative dynamic modulus with freezing and thawing cycles for the recycled concrete using aggregates from non-AE concrete. All of the concrete were poor in resistance to freezing and thawing. Increasing the air content or lowering the water-cement ratio in recycled aggregate concrete did not improve the resistance sufficiently.

SUSTAINABLE DEVELOPMENT

Concept

Of all the processes in the construction industry, cement manufacture releases the largest quantities of carbon dioxide. Also, to make concrete a sustainable material, the cement in concrete must be recycled. There has been some progress in recycling aggregate from demolished concrete. However, this paper proposes a change in this approach, to place primary emphasis on recycling the cement materials from demolished concrete -- in other words, to aim to reclaim the fine powder containing as much cement components as possible. This would result in the recycling of good quality aggregate as well.

Reclaimed Cement

Table 6 shows the chemical composition of normal portland cement and aggregate powder. The chemical composition of aggregate powder was estimated from the chemical composition of powders produced by several aggregate recycling factories (1). Table 7 shows the chemical composition of recycled powder for different aggregate ratios in the recycled powder. They are calculated from Table 6.

One method of reclaiming aggregate from concrete is to embrittle the paste components by a thermal treatment (6). After heating concrete rubble up to 300℃, the separation of cement matrix from aggregate by ball mill is tested. According to the reports (7), the recycled aggregate crushed after the thermal treatment fulfills the Japanese Industrial Standard (4) for concrete aggregate, for both coarse aggregate and fine aggregate, and the coarse aggregate is almost completely unbroken. The aggregate ratio of the powder is estimated at 35%. This is the result of grinding the aggregate, and so future studies will be conducted on the assumption that the aggregate ratio can be reduced to 30%.

Table 8 shows the results of how the quantity of limestone can be reduced when the recycled powder with an aggregate ratio of 30% shown in Table 7 is used as clinker raw material. The value for Na_2Oeq slightly exceeds the standard for normal portland cement, but in principle recycling of powder to make cement is thought to be possible.

Evaluation of Recycling

Under the assumption that the recycled powder above can be recycled to make cement, the resources, energy and carbon dioxide emissions for a material flow of 1 m^3 of concrete are evaluated. The cement was the aforementioned normal portland cement and recycled portland cement, and the conditions were those shown below. Carbon dioxide emissions were expressed by the commonly used measure of carbon mass (kg-C).

[Cement manufacture]

Resources: Mining loss for limestone, clay and silica = 0%

Energy: For mining and pulverizing limestone and silica = 42 kJ/kg (8)

For calcination = 2954 kJ/kg of clinker (9)

= 1882 kJ/kg of clinker raw material

In calculating the energy required to calcine recycled cement, in order to reflect the loss of decarboxylation energy and the loss of clinker raw materials, the firing energy was converted to the value per unit of clinker raw materials, as shown above.

Carbon dioxide emissions:

From limestone = 0.12 kg-C/kg (9)

From calcination = 0.0626 kg-C/kg of clinker (9)

From distribution = 0.0025 kg-C/kg of cement (10)

[Aggregate production]

Aggregates are crushed stone and crushed sand. The conditions for each are shown below.

Resources: Mining loss for crushed stone and crushed sand = 30%

Pulverization loss for crushed stone and crushed sand = 10%

Energy: For manufacture of crushed stone and crushed sand = 42 kJ/kg (8)

Carbon dioxide emissions:

From manufacture of crushed stone and crushed sand = 0.00189 kg-C/kg (10)

From distribution of crushed stone and crushed sand = 0.00056 kg-C/kg (10)

[Concrete demolition and thermal treatment]

Under the assumption that the demolished concrete is transported to a place near the factory and then fired to 300℃ and pulverized, the conditions for the demolition and heating processes are shown below.

Energy: For heating process = 0.8 kJ/kg℃ × 300℃ × 1.25

= 300 kJ/kg of concrete

For demolition, transport and pulverizing = 42 kJ/kg (8)

Carbon dioxide emissions:

From heating process = 0.0161 kg-C/MJ (11)

From pulverizing = 0.00189 kg-C/kg of concrete (10)

From transport = 0.00056 kg-C/kg of concrete (10)

[Recycled concrete]

Table 9 shows the concrete mixture proportions.

Fig. 11 shows the material flow, energy and carbon dioxide emissions per 1 m^3 of concrete studied under the conditions shown above.

First, the use of new materials and the use of recycled materials were compared in terms of resources. Table 10 shows the consumption of resources for the major components. When the cement in concrete is recycled, the amount of limestone mined decreases to 61% compared with when new materials are used. Clay and silica are not needed; the quantity of iron slag consumed drops to 58%, and the quantity of stone for aggregate drops to 9%. Moreover, the quantity of stone for aggregate that is discarded is reduced from 774 kg to 71 kg (Fig. 11). When cement is recycled, of the 474 kg of recycled powder, 287 kg of powder is left over. This is small in comparison to the quantity of new stone for aggregate that is discarded, and it indicates that in terms of quantity the refining of recycled powder is possible. In this way, recycling of the cement in concrete will make it possible to both conserve resources and reduce the destruction of the natural environment caused by the mining of resources.

Table 11 also shows a comparison of energy requirements. When cement is recycled, the demolished concrete is heated, and so energy requirements are 58% greater than when new materials are used. In this study, it was assumed that concrete would be recycled at a cement factory, and so some reduction of energy requirements can be anticipated though the use of waste heat. More radically, improvements in cement calcinating processes through the use of different raw materials are also anticipated. However, in the current situation, an increase in energy requirements is judged to be unavoidable.

Table 12 shows a comparison of carbon dioxide emissions. When cement is recycled, carbon dioxide emissions from cement manufacture are reduced by 29%. Even if the increase in carbon dioxide emissions due to the heating process is factored in, this still represents an overall decrease of 11%. The problem of carbon dioxide emissions is a serious one for the global environment. At the Kyoto conference on global warming held in 1997 (Third Conference of the Parties to the United Nations Framework Convention on Climate Change), Japan's target for reduction of CO_2 emissions was 6%. Reducing carbon dioxide emissions due to cement manufacture, in which large quantities of carbon dioxide fixed in limestone are discharged, would have tremendous significance.

As we have seen, a closed recycling system of concrete recycling, in which cement and aggregate are recycled from demolished concrete, would increase energy requirements somewhat, but it would also conserve resources, reduce the destruction of the natural environment due to the mining of these resources and reduce carbon dioxide emissions. Even recycling concrete aggregate alone would enable conservation of resources and reduce the destruction of the natural environment that results from the mining of these resources. However, it would not reduce carbon dioxide emissions, and so this would be only a slight improvement over the current reuse of this aggregate as road base coarse and foundation material. Surely concrete recycling that includes cement and is aimed at reducing the amount of limestone used to make cement is the approach that recycling should take in the 21st century.

SUMMARY

(1) In recycling demolished concrete, change is necessary from reuse as a road foundation material to recycling for concrete aggregate. Furthermore, recycling should include cement.

(2) The recycled aggregate does not satisfy the Japanese Industrial Standard requirements for concrete aggregate.

(3) The quality of recycled concrete as aggregate depends on the quality of original concrete. The recycled aggregate was suitable for concrete within the strength level of original concrete without special further treatment. The resistance to freezing and thawing of recycled concrete was not satisfactory unless the original concrete was air-entrained concrete. The amount of mortar adhered to the recycled aggregate had little affect on the strength and durability of recycled concrete.

(4) For reducing carbon dioxide emissions that causes global warming, and for making concrete sustainable, it is desirable that concrete recycling includes cement as well.