The Japan Society of Civil Engineers (JSCE) in 2010 selected as a priority research task the theme entitled "Survey of technology for demolition, reuse, and repair of concrete structures taking CO_2 reduction into account – zero emissions repair work and CO_2 uptake technology for concrete." In response, the Concrete Committee of JSCE set up on June 1, 2010 the "Subcommittee for survey of technology for demolition, reuse, and repair of concrete structures taking CO_2 reduction into account" (Subcommittee 219) in order to carry out this research effort. This paper is a summary of the subcommittee's findings.

1 Introduction

Public concern over environmental problems, in particular global warming, has been increasing. As a result, civil engineering structures are also being analyzed for their impact on the environment – though this is still only in its initial stages. The Standard Specifications for Concrete prescribe that concrete and concrete structures shall be designed with adequate consideration of their impact on the environment, but although some examples are given, there are no specific evaluation methods or environmental consideration methods that would allow sufficient measures to be taken. As the large quantity of social infrastructure stock that was constructed during the period of high economic growth in Japan enters a period of massive renewal, maintenance, and repair, it is anticipated that the number of civil engineering structures being demolished will gradually increase in the future. There is an urgent necessity to establish measures for problems such as disposition of large quantities of demolished concrete, the lack of sufficient recycling facilities, and the environmental impact of CO_2 emissions during transport and processing, etc. On the other hand, if chunks of demolished concrete are reused as recycled aggregates, then CO_2 will be immobilized by carbonation of the concrete on the fracture surfaces and in the fine powder newly generated in the process of producing the recycled aggregates, so a CO_2 reduction effect can be expected.

Therefore, research in the form of a survey was carried out by the subcommittee with the objective of proposing methods of evaluation aiming for a total reduction of CO_2. Technology for efficiently immobilizing CO_2 upon demolition of concrete structures was also surveyed, while methods of reducing environmental impact, such as by reducing CO_2 and reducing waste during repair, were investigated.

2 Environmental Considerations in the Selection of Repair Methods for Existing Concrete Structures

In this section, the results of our investigations into how environmental impacts can be taken into account when selecting repair methods for existing concrete structures are described, based on the results of case studies.

2.1 Repair method case studies

A literature survey was carried out into the cost, service life, and CO_2 emissions for the various repair methods considered in the case studies. Estimations reflecting the results were carried out for the life cycle cost (LCC) up to 100 years after construction, life cycle emissions of CO_2 ($LCCO_2$), and life cycle waste quantity (LCW) assuming (1) a pretensioned PC simple T-beam bridge (spray zone, 0.1 km from the sea) and (2) RC box culverts (0.1 km and 0.5 km from the sea). Structural deterioration was simulated by calculating rates of steel corrosion considering the variation in cover depth and the probability of steel corrosion. From the results, the amount of repair work required was calculated. The permeation of chloride ions was based on Fick's law of diffusion, with the threshold concentration of chlorides for corrosion was assumed to be 1.2 kg/m^3. The repair methods included surface coating (preventative), electrical corrosion prevention (preventative), removal of chloride + surface coating (preventative), patch repair + surface coating (preventative), and patch repair + surface coating (corrective). Preventative repairs were carried out on the whole structure when the average conentration of chloride ions around the rebars reached 1.2 kg/m^3, while corrective repairs were carried out successively only on those parts with significant deterioration.

2.2 Integration of cost and environmental impacts

To integrate different indices, a method in which the various indices are converted into monetary terms might be considered. As the monetary value of $LCCO_2$ was about 1% of LCC, that would give no incentive to reduce adverse environmental impacts. However, in the maintenance of the social infrastructure, it is not sufficient to simply make decisions based on economic rationality, and it is necessary to take into consideration local and global environmental impacts. Therefore, a method of integration was investigated based on ratios against the standard method (patch repair + surface coating (corrective) by renewing the coating material every 20 years). When selecting a repair method from among several options, first a method for which the $LCCO_2$ ratio and the LCW ratio to this standard are less than 1.0 is selected. Then, using the indices with respect to the selected method as shown by the following equations, the ultimate choice of a method can be made. An example of the trial calculation results is shown in Table 1.

$I_{sum} = a \times \text{LCC ratio} + b \times \text{LCCO}_2\text{ ratio} + c \times \text{LCW ratio}$ (*a, b,* and *c* are relative weighting coefficients)

$I_{times} = \text{LCC ratio} \times \text{LCCO}_2\text{ ratio} \times \text{LCW ratio}$

$$I_{BC1} = \frac{A_1(1-\text{LCCO}_2\text{ ratio}) + B_1(1-\text{LCW ratio})}{\text{LCC ratio}} \quad \text{or} \quad I_{BC2} = \frac{A_2 \times 1/\text{LCCO}_2\text{ ratio} + B_2 \times 1/\text{LCW ratio}}{\text{LCC ratio}}$$

(A_1, B_1, A_2, and B_2 are the relative weighting coefficients of the $LCCO_2$ ratio and the LCW ratio with respect to the LCC ratio)

Table 1 Example of trial calculation results for integrated indices

Repair method	RC culvert							
	0.1 km from sea				0.5 km from sea			
	I_{sum}	I_{times}	I_{BC1}	I_{BC2}	I_{sum}	I_{times}	I_{BC1}	I_{BC2}
Electrical corrosion prevention	1.69	**0.19**	0.56	**5.38**	2.53	0.46	0.34	2.20
Surface coating (reapply top coating every 10 years)	**0.93**	**0.19**	**1.11**	5.28	**1.04**	**0.25**	**0.95**	**4.08**
Surface coating (complete renewal every 20 years)	1.41	0.49	0.48	2.03	1.39	0.48	0.49	2.09

Overall, surface coating (reapply top coating every 10 years) is generally superior, but in the case of I_{times} and I_{BC2}, electrical corrosion prevention is equal or superior. It can be said that I_{times} and I_{BC2} are indices that are highly sensitive to the effectiveness of adverse environmental impact reduction. In fact, a certain amount of cost is permissible to reduce adverse environmental impact, but it is considered that an upper limit value can be set. In other words, it is considered that a general method is to make a primary selection of a repair method whose cost is less than the upper limit value and for which the ratio of environmental impacts is 1.0 or less, and then judge the remaining repair methods using the integrated indices. In this case it is considered that the repair method should be selected using I_{times} or I_{BC2} to increase the sensitivity to environmental impact.

3 CO_2 Uptake by Demolished Concrete

In this section, the results are presented of investigations into the significance of quantitively evaluated CO_2 uptake by crushed waste concrete (demolished concrete), the estimated amount of demolished concrete, the properties of the demolished concrete according to manufacturing process, the results of a national survey on CO_2 uptake, and methods of visualizing CO_2 uptake by demolished concrete.

3.1 Estimated quantity of demolished concrete and its properties according to manufacturing process

Various methods for estimating the quantity of demolished concrete produced, based on the service life of structures and on budgets for and the amount of new construction, were summarized. The actual quantity of demolished concrete obtained from a survey was compared with these estimated quantities. This demonstrated that estimated quantities based on new construction budgets and the amount of new construction are more accurate in the short term than the estimated quantity based on service life.

Next, equipment and manufacturing processes for recycled crusher run were investigated. Then the properties of the recycled crusher run particles, such as their particle size distribution, the finer particle content, the density, the water absorption, and the abrasion loss were investigated. The results show that although the particle size distribution of currently used recycled crusher run is almost identical to the distribution proposed by the Japan Road Association Handbook on Pavement Recycling, it contains slightly higher amounts of finer particles than recommended by the Japan Road Association.

3.2 Quantification of CO_2 uptake by demolished concrete

The fundamental theory of CO_2 uptake by demolished concrete was summarized by outlining the carbonation reactions of cement hydration products. Also, the theoretical quantity of CO_2 uptake based on carbonation theory was calculated on the basis of an assumed chemical composition of the cement and an assumed concrete mix proportion.

The quantity of CO_2 uptake by demolished concrete and its fixation rate vary depending on the particulate size, the quantity of cement paste in the particles, and the environmental exposure conditions (particularly humidity). Here the results of a fundamental investigation using mortar are summarized. The results indicate that the smaller the particle size and the higher the water-cement ratio, the faster the progress of carbonation. Also, the amount of CO_2 uptake for actual recycled crusher run particles smaller than 5 mm was investigated. This report verifies the results of the national survey by the National Institute for Land and Infrastructure Management, which shows that not only smaller particles but also larger particles of demolished concrete combine with a substantial amount of CO_2. In addition, a literature survey was carried out to investigate a joint research project in the four Scandinavian countries. The project report includes methods of quantifying the amount of CO_2 uptake by demolished concrete and methods of reflecting the amount in the $LCCO_2$.

3.3 Visualization of CO_2 uptake by demolished concrete

A method of visualizing the uptake of CO_2 by demolished concrete was proposed and investigated. The sludge cake from a ready mixed concrete plant was used in the experiment. The fresh sludge cake was placed into a gas sampling bag and CO_2 was blown into the bag. As time passed, deflation of the bag can be observed due to the CO_2 uptake. A video of the experiment shown in Photograph 1 can be seen at the following URL: http://www.jsce.or.jp/committee/concrete/download/CO2.wmv.

Photograph 1 CO_2 uptake visualization test result (bag method)

4 Conclusion

Based on the research results given in above section 2, an integrated method based on relative environmental impact was proposed for taking environmental effects into consideration when selecting repair methods. A specific repair method selection procedure was proposed using the LCC ratio, the $LCCO_2$ ratio, and the LCW ratio. Using these ratios as a basis, it is necessary to create a system for simply calculating the quantity of CO_2 emitted and the quantity of waste generated. For example, if approximate values of the quantities of CO_2 emissions and waste generated can be obtained for each type of repair method and for each scale of repair work, it will be possible to simply calculate the quantities of CO_2 emissions and waste generated by a particular repair. It will be necessary to accumulate this type of data in the future.

In addition, based on the research results in section 3, a procedure for calculating the quantity of CO_2 immobilized after demolition of concrete until reuse was proposed. This is a calculation of an approximate quantity of CO_2 immobilized during storage of the demolished concrete and the percentage that passes a 5mm sieve. It should be noted, however, that this CO_2 uptake after demolition is an additional phenomenon that takes place during the process of demolition and reuse; that is, after the concrete or concrete structure has gone out of service. Neutralization (carbonation) is not recommended during the service phase of a concrete structure.

Finally, generalizing the above, a procedure for evaluating the environmental impacts of concrete structures was proposed. As a rule, evaluation of environmental impacts should apply to the full life cycle, from planning and design up to demolition and disposal.

However, in practice, it is considered possible to implement it at any one stage, such as during construction, repair, demolition, disposal, etc.

(Note) The subject of this research was concrete structures that had entered service, so construction was not considered. Consequently, within the scope of this research, it is not possible to substantially analyze the full life cycle of concrete or concrete structures. However, when considering future environmental impacts at the time of repair or at the time of demolition or reuse, the life of the concrete or the concrete structure from that point onward is within the scope of this work. This means that the terminology LCC, $LCCO_2$, and LCW can also be used for determining the costs, quantities of CO_2 emissions, and quantities of waste generated for the repair process as well as the demolition and reuse processes. This is a deviation from the original definitions, but one that we consider permissible.