Boosting seafood production with recycled industrial by-products

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Reefs of coal-ash cement blocks generate upwelling that enhance marine productivity

OUTLINE OF THE CONCEPT

The current global fish haul is about 300 million tons a year, while the stock of nutrients "in the oceans has the potential to support 70 trillion tons of life. Thus, there is a potential for boosting the productive capacity of the sea. At the same time, undersea ridges are where reef ecosystems form, and these are highly productive fishing grounds. This paper illustrates how the dream of re-using a long-neglected industrial by-product is coming to reality in a field trial aimed at boosting this productive capacity.

Large eco-friendly blocks comprising mainly coal ash are mass-produced (Photo 1) and stacked on the seabed to form undersea terrain in the shape of natural reefs. (Fig. 1) These reefs, which may extend up to few kilometers in length, are suitable for deep, low-productivity waters off the coast of Japan where the seabed is flat. The structures cause upwelling, forcing water with a high content of nutrients to rise from the depths to the euphotic zone; this is the region shallower than the compensation depth at which the oxygen produced by phytoplankton through photosynthesis is equal to that consumed by phytoplankton. After rising to the euphotic zone, nutrients such as nitrates and phosphates help phytoplankton to proliferate. Since phytoplankton form the bottom rung of the aquatic food chain, their proliferation leads to greater zooplankton and fish numbers, thus boosting marine production.

To verify the feasibility of the concept and its effectiveness, a field trial is being implemented principally by Marino Forum 21 (MF21) with a subsidy from the Fisheries Agency.

With the world facing such problems as shortages of food, environmental destruction in coastal regions through reclamation using industrial by-products, and global warming due rising carbon dioxide emissions, it is more important than ever to make effective use of resources. This concept offers the possibility of recycling industrial by-products that have conventionally been discarded while simultaneously solving some of these problems. As such, it is coming to international attention.

WORLD POPULATION GROWTH AND THE FOOD PROBLEM

The underlying cause of the environmental, energy, and food problems now facing mankind is world population, which has already reached 6 billion and is increasing annually by 100 million. In addition to the energy shortages and pollution this growth is causing, shortages of food are likely to afflict us in the 21st century. Currently 800 million people in the developing

Photo 1 Coal-ash cement block (a 1.6 m cube weighing 6 tons) being moved with a forklift truck

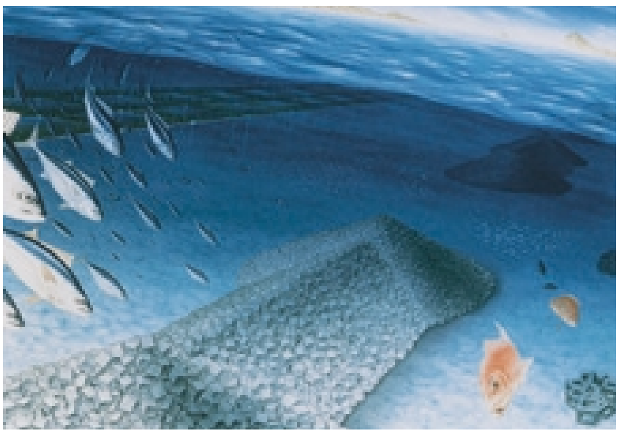

Fig. 1 Impression of an artificial submarine Super Reef structure built with recycled blocks

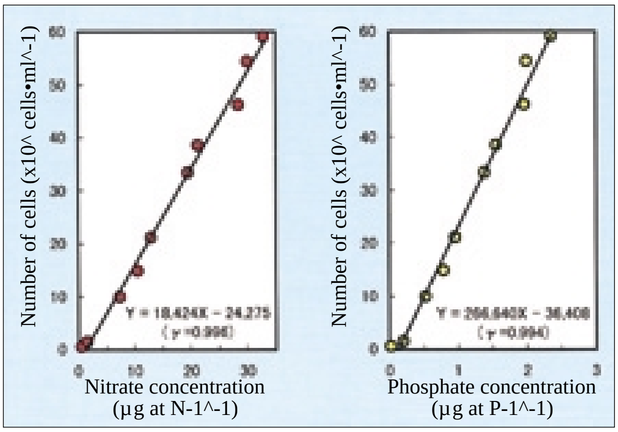

Fig. 2 Relationship between concentration of nutrients and the number of phytoplankton cells

Source: Marine Science and Technology Center

nations of Africa and Southeast Asia face starvation, though if food were shared equitably, supply and demand would probably be in balance at the present time. Further, despite improvements in breeds, annual grain production has leveled off at 2 billion tons. Even if more farmland were developed, this would in turn lead to deforestation and over-use of fertilizers and pesticides, which pollute groundwater and air. Thus, higher grain yields cannot be anticipated, and anyway as people's tastes change the demand for livestock farming disturbs the balance between supply and demand. As a result, there is concern that supply will not keep up with the demands of a sharp rise in world population during the 21st century.

On the other hand, even if we could estimate the ultimate human capacity of the earth, it would be difficult to control population growth. In fact, world population has increased by a remarkable six-fold in the past 200 years. To support this increasing population, mankind has developed domestic animals and plants for food, and today the mass of humans and livestock makes up about 50% of all large animals on the earth. It is clear that we humans control the destiny of all living things, and we are responsible for finding a solution to these problems.

JAPAN'S PROBLEM OF FOOD SUPPLY AND DEMAND AND SEAFOOD PRODUCTION

With growing concern about a world-wide food shortage, it is not acceptable by international standards for Japan, with a population accounting for only 2% of the world total, to continue as the world's largest food importer. Japan's economic strength and the capacity of other countries to export food are both limited. On the other hand, Japan's calorie self-sufficiency dropped from 91% in 1960 to 42% in 1996. With food now regarded as a strategic resource around the world, Japan is in the rather dangerous position of seeing not only its energy supply and defense capabilities, but also its food security, in the hands of other nations.

One answer to this problem is for Japan to consider ways of increasing food production by taking advantage of natural production within its exclusive 200-mile economic zone, which is an area ranked six in the world for its potential. To increase seafood production, it is necessary to encourage the growth of phytoplankton and marine algae. On the other hand, the growth of phytoplankton in the euphotic zone is limited because there is a low concentration of nutrients.

In 1969, Dr. Riser in the U.S. presented a paper in the Science in which it was noted that 50% of all fish production occurs where water rises upward, although this accounts for only 0.1% of the total sea area. His paper focused attention on the relationship between the concentration of nutrients and marine organism production, and many researchers verified the very high correlation between nutrient concentration and the proliferation of phytoplankton. (Fig. 2) With collaboration from fisheries experimental stations in various prefectures, MF21 has taken water samples from both the surface layer and lower layers off the coast of Japan, and has measured the concentration of nutrient salts. Further, MF21 propagated phytoplankton in these samples and demonstrated that it would be possible to encourage phytoplankton growth off the coast of Japan by mixing the water masses of the surface layer with those of the lower layers.

TECHNOLOGICAL CHALLENGES AND HISTORY OF THEIR RESOLUTION

The feasibility of the concept depended on solving many challenges: (1) would it be possible to use artificial structures of some kind to set up the upwelling currents needed for commercial fish production, (2) would it be possible to develop highly productive fishing grounds around artificial upwelling, (3) would it be possible to make safe use of industrial by-products in undersea structures on a scale equivalent to that of natural reefs, and (4) would it be possible to economically build such structures in the desired shapes in deep water? Since announcing the concept in 1984,

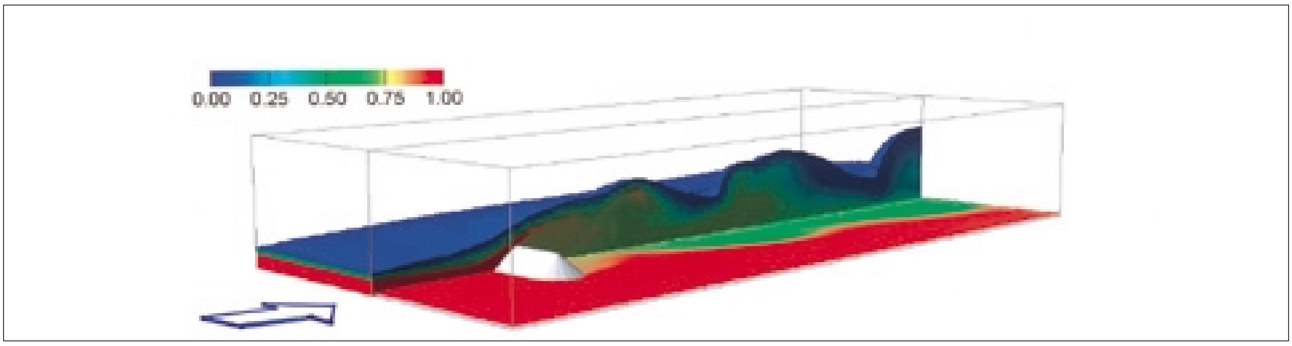

Fig. 3 Typical result of a three-dimensional analysis of upwelling generated beyond an undersea structure in stratified flow

MF21 and other companies have joined forces to overcome these challenges. Finally, in fiscal 1995, a field trial aimed at realization of the concept was launched as a national project entitled the Development of Super Reef Building System.

To study the scale and arrangement of the underwater structures needed to set up the required vertical flows of water, a highly productive natural reef was modeled to allow studies of what constitutes a good fishing ground. Hydraulic experiments and numerical analysis were carried out with stratified flows to clarify how upwelling develop around natural reefs. In the final analysis, it was shown that very strong upwelling form when the total length of a high structure in a direction orthogonal to the horizontal flow is 4-6 times the structure's height. (Fig. 3) Further Research and Development into Large-Scale Artificial Fishing Grounds based around Upwelling Currents was commenced in fiscal 1989 as a feasibility study for forming fishing grounds around artificial upwelling.

Based on the results of these studies, MF21 started a Pilot Project for Generating Artificial Upwelling Currents in the Uwa Sea, Ehime Prefecture, in fiscal 1991. In this study, it was verified that artificially developed upwelling currents aid the growth of phytoplankton, zooplankton, and fish and increase marine productivity.

DEVELOPMENT OF TECHNOLOGY FOR MANUFACTURING COAL-ASH CEMENTED BLOCKS

The concept described requires the construction of large-scale structures akin to mountain ranges under the sea. The use of massive amounts of natural stone and ordinary concrete for such structures in resource-poor Japan would accelerate the depletion of our natural resources and cause environmental destruction. Given this situation, MF21 initiated Research and Development of Coal-Ash Cemented Blocks in 1986 to study the feasibility of new materials. The strength and durability of coal-ash cement blocks including a hardener were tested, and it was verified from a safety viewpoint that they met the water pollution control standards. In fiscal 1992, the use of the blocks was authorized in the Design Guidelines for Development of Coastal Fishing Facilities issued by the Fisheries Agency.

After pursuing further quality improvements and cost effectiveness issues, a new manufacturing technology was developed in 1994. Conventionally, coal-ash cement blocks are manufactured and controlled for quality according to the flow value specified in JIS A 5201 in the same manner as for ordinary mortar. The new manufacturing process, on the other hand, controls quality on the basis of water content, using a value close to the optimum water content obtained from the soil compaction tests specified in JIS A 1210. The mixture is then transformed into a special fluid by strong shaking. (Photo 2) The use of this technology makes it possible to obtain comparable compressive strength with just two-thirds of the amount of cement used in the

Photo 2 New technology for manufacturing coal-ash cement blocks

A mixture of coal-ash and cement combined with an optimum amount of water (left); the mixture compacted and transformed into a special fluid by shaking (right)

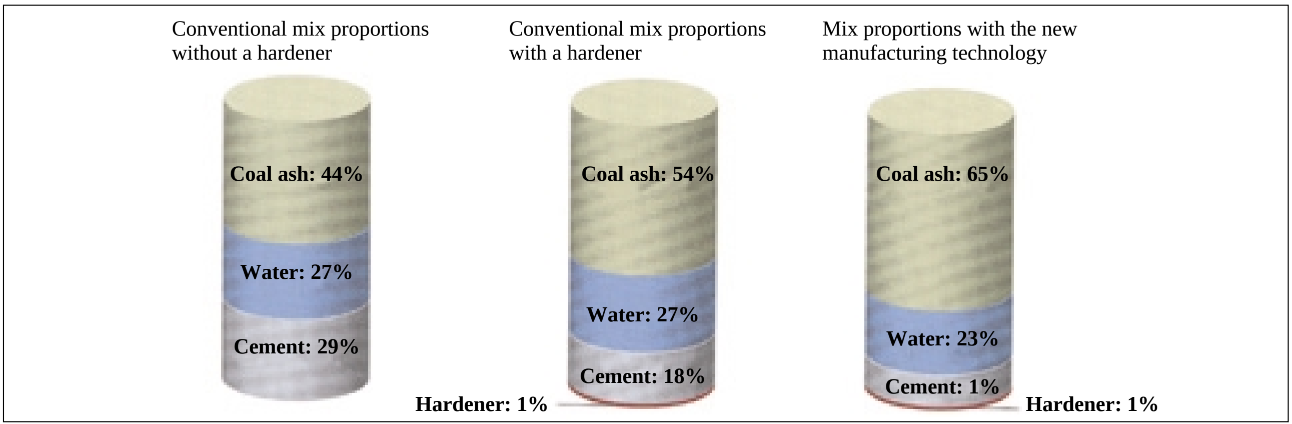

Fig. 4 A comparison of typical mix proportions for coal-ash cement blocks with a comparable compressive strength (20 N/mm^2)

conventional method. In addition to the usual characteristics, the mixture produced by this process is convenient to handle because it does not stick to containers during mixing and transport, is resistant to cracking in drying, and, as a result, requires no special protective measures. A quick comparison of typical mix proportions with the new technology for coal-ash cement blocks of comparable compressive strength (20 N/mm^2) with conventional mix proportions with and without a hardener indicates that an order of magnitude reduction in cement content is achieved by the new technology. (Fig. 4)

To mass-produce the coal ash blocks from a raw material that exhibits sharp fluctuations in quality, it was essential to develop a system that allows for rapid adjustment of the mix proportion. In the course of research work on this, it was found that there are strong positive correlations between the fine-particle-to-water ratio and compressive strength (Fig. 5), and also between cement content and strength. A mix proportion decision system was developed in which the optimum fine-particle-to-water ratio is determined based on these characteristics, and then the compressive strength at the age of 28 days is forecast. The hardened coal-ash blocks are then manufactured with the required compressive strength by adjusting the cement content.

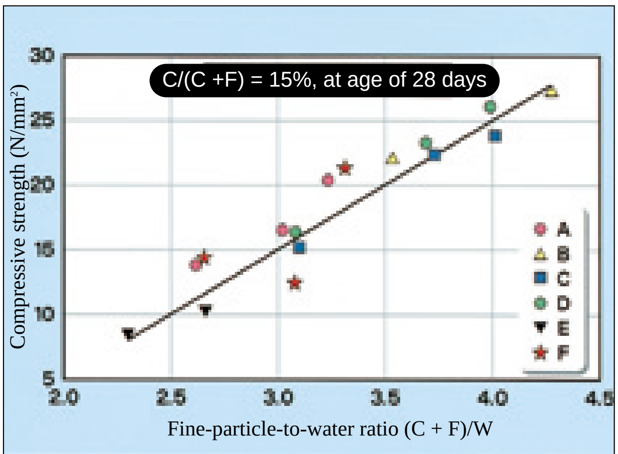

Fig. 5 Positive correlation between fine-particle-to-water ratio and the compressive strength of coal-ash cement blocks, without reference to ash type

TECHNOLOGY FOR ACCURATELY PLACING LARGE BLOCKS UNDERWATER

It was necessary to develop a technology for building structures akin to mountain ranges on the seabed at depths of 80 m or more while coping with rapid currents. Because current configurations may change during the construction work, time-consuming efforts are necessary to cope with this, leading to reduced accuracy and cost effectiveness. One construction method that was considered promising entails dropping blocks freely from bottom opening barges. (Photo 3) However, there were no existing reports on building such large structures in deep water by this method, and there were questions with regard to whether the desired shape could be achieved. To verify the feasibility of this work method, various hydraulic experiments and numerical analyses were carried out, and as a result it was learned that it was workable if the drift of blocks was properly forecast.

In constructing structures such as these in deep waters, it is also necessary to have a method of accurately measuring the work in progress. A sounding system comprising RTK-GPS, a single-beam echo-sounder, and a clinometer was developed. To survey the seabed terrain, a variety of advanced techniques were adopted because it proved difficult to obtain the information using conventional technology; for instance, the height of the structure above the seabed was

Photo 3 Blocks being dropped from open-bottomed hopper barge accurately located using DPGS

Photo 4 Unprotected blocks stored in temporary yard

measured with a narrow multi-beam echo-sounder, side-scan sonar, and ROV (Remotely Operated Vehicle; an underwater robot with TV camera). Further, measurement accuracy was improved by increasing the survey frequency.

PRESENT STATUS OF FIELD TRIAL

The field trial is under way in waters with a depth of 80 m off Ikitsukishima Island in Nagasaki Prefecture. This is the national project Development of Super Reef Building System, and it is scheduled to continue for 6 years from fiscal 1995. The plan called for the manufacture of about 5,000 blocks, each a 1.6 m cube weighing 6 tons, from coal ash of greatly varying quality. Mass-production over the past three years using a new manufacturing technology has led to about 3,500 blocks being fabricated so far. (Photo 4) The structure is shaped like a mountain range with a ridge linking 14m conical peaks at each end. As already described, construction accuracy was increased by dropping the blocks from a location calculated in consideration of current direction and velocity. A total of about 2,000 blocks have been laid on the seabed in the past two years. The results of a survey with a precision echo-sounder and ROV indicate that the resulting structure has exactly the shape seen in hydraulic model experiments, with an accuracy of a few meters in height and coordinates of one summit. (Fig. 6)

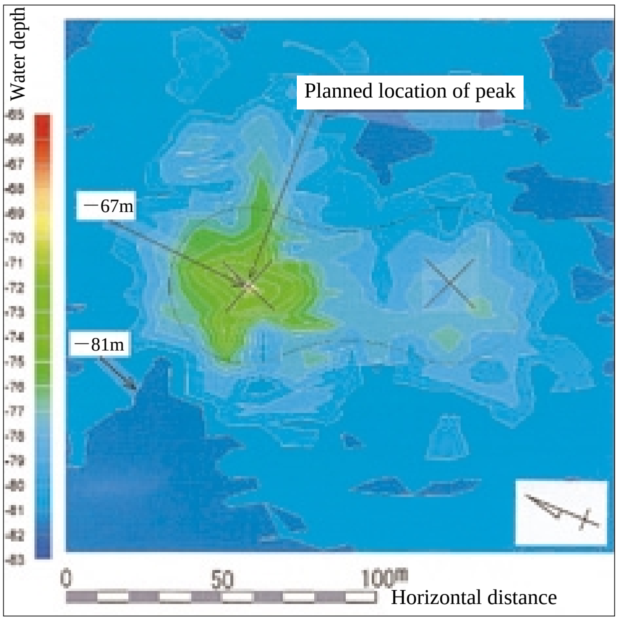

Fig. 6 Super Reef under construction, reaching a height of 20 m with about 2,000 blocks (precision echo-sounder measurements)

Although the mound is still only 40% of its planned size, a sample survey carried out with a fishing vessel revealed that the frequency of fish sightings and fish hauls have both increased. This indicates that we are on the way do developing a good new fishing ground. Further, in a scant 10 months after installation of the blocks, their surfaces were closely packed with barnacles and lug worms. Vast shoals of fish were observed in the cracks between blocks, as well as around and in layers above the mountain range structure. It is therefore concluded that a highly productive reef ecosystem is being formed. (Photo 5)

EFFECTS OF REALIZATION

This new concept, when it turns commercial, will have the effects outlined below while aiding the development of both the marine products and electric power industries.

- In addition to encouraging the proliferation of phytoplankton, the formation of a reef ecosystem will increase the amount of protein available to fish


Photo 5 Fish shoaling around Super Reef within 10 months of installation; photo taken by ROV

using the energy of nature.

- Recycling coal ash reduces the need for coal ash disposal sites and thus helps to protect the environment. Since land reclamation is a conventional use for such waste, highly productive seaweed beds, tidelands, and coral reefs will be saved. A 1,000 MW coal-fired power plant operating for 30 years would produce coal ash that would require 110 hectares of shallow water for disposal, resulting in huge loss of precious ecosystems.
- The proliferation of phytoplankton leads to the fixing of carbon dioxide; carbon dioxide is taken up from the water by plant growth, and to compensate carbon dioxide from the atmosphere dissolves into the water. Thus this concept can also be expected to control global warming. According to a trial calculation, if all the coal ash generated by a 1,000 MW coal-fired power plant is used to build such artificial structures, it would be possible to fix more than half the amount of carbon dioxide generated by the plant.
- The development of such seafood production centers through the recycling of industrial by-products will provide the construction industry with a large new market.

EXPECTATIONS FOR COMMERCIALIZATION

As explained, this concept simultaneously boosts seafood production while helping to preserve the environment by recycling an industrial by-product. Therefore, commercialization will require cooperation among many disparate authorities. Considering great benefit that the concept could bring to the people of Japan, the concept should be brought into use outside the usual framework of laws and budgets. Further studies on the introduction of the PFI (Private Finance Initiative) or the implementation of the venture under the direct control of the government will be necessary if advantages such as increased seafood production, the recycling of waste, preservation of the environment are to be consistently achieved using this concept.

The total amount of coal ash generated a year will double to 12 million tons by 2005. If this ash is not recycled, the productive output of Japan's shallow waters will be lost. Indeed, in resource-poor Japan it is important to recycle the slag and ash discharged from sludge incinerators as well as coal ash, and this method may also be applicable in this area.

Recycling, food production, and environmental preservation are important challenges that are common to the whole of humanity. We hope that this concept will become a reality and find use on a worldwide scale.