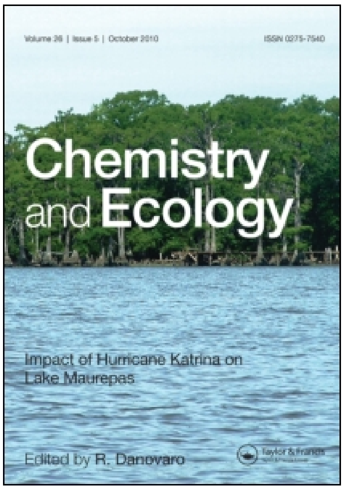

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APPLICATION OF HIGH-VOLUME FLY ASH CONCRETE TO MARINE STRUCTURES

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A new material with high content of fly ash named 'Ashcrete' has been developed. To examine the applicability of Ashcrete to marine structures, strength characteristics, resistance to sea water attack, and safety in the marine environment have been studied. The following results have been obtained:

1) The strength characteristics of high-volume fly ash concrete depend upon the type and proportions of chemical activators as well as curing conditions.
2) Ashcrete using sodium chloride (NaCl) as a chemical activator shows high initial strength and good strength development with age.
3) Ashcrete containing NaCl activator shows good resistance to sea water from the viewpoint of its strength characteristics, volume changes and microstructures.
4) Since 1980 many types of large-scale artificial reefs made of Ashcrete have been installed in the sea. As a result of long-term studies and underwater observations, the Japanese Government has demonstrated the durability of the material, safety in the marine environment and attractiveness to fish.
5) It is therefore proposed that Ashcrete might be used in constructing large-scale sea mounts in deep water for the purpose of generating upwelling.

KEY WORDS: flyash, marine structures, fishery developments, Japan

INTRODUCTION

Since Japan imports 98% of its demand for oil from foreign countries, it suffered severely from the energy crisis in the mid-1970's because of the oil embargo at that time. In order to diversify energy sources coal-fired electric power stations have been promoted. In Japan, combustion of coal generates a large quantity of fly ash, of which about 54% (2.2 million tons per year) is discarded without being put to any use. Therefore, there is an urgent need to examine possible uses for fly ash.

Meanwhile, 200-mile exclusive economic zones have been proclaimed world-wide and the focus of the fishing industry in Japan has shifted from catching, to nurturing and harvesting, to ensure a stable supply of marine resources from its home waters. The Fishery Agency of the Japanese Government has inaugurated the Coastal Fishing Grounds Enhancement and Development Program (abbreviated 'Ensei' Program), whose objective is to develop methodologies for constructing fishing grounds of much enhanced productivity.

The author of this paper has proposed the use of high-volume fly ash concrete named 'Ashcrete' to support large-scale fishing ground development projects under way in Japan. This paper discusses strength, resistance to sea water, microstructure, and safety features demonstrated by leaching tests of Ashcrete. As a result of more than 10 years research and tests. Ashcrete that meets the criteria set forth by the Government has now become one of the officially qualified materials for major public construction projects such as fishing ground construction in Japan.

FLY-ASH CONCRETE

The ash which is precipitated from the flue gases of a pulverized coal boiler is generally termed fly ash. A photograph of fly ash taken with a scanning electron microscope (SEM) is shown in Figure 1. For the most part, fly ash consists of tiny glass-like spherical particles less than 50 μm in size.

The main crystallized minerals found in fly ash are alpha-quartz and mullite, with a very small quantity of free lime and anhydrite gypsum. Ashcrete is a concrete of which all or part of the aggregate in a plain concrete has been replaced with fly ash. If about 54% fly ash and 15% cement are mixed with water, the Ashcrete creates a high-strength, stable concrete. Moreover, if the proper activator is used, the Ashcrete gains high initial strength. This report presents the results of the tests of Ashcrete whose 28-day compressive strength was within the range of 100–400 kg cm^{-2}.

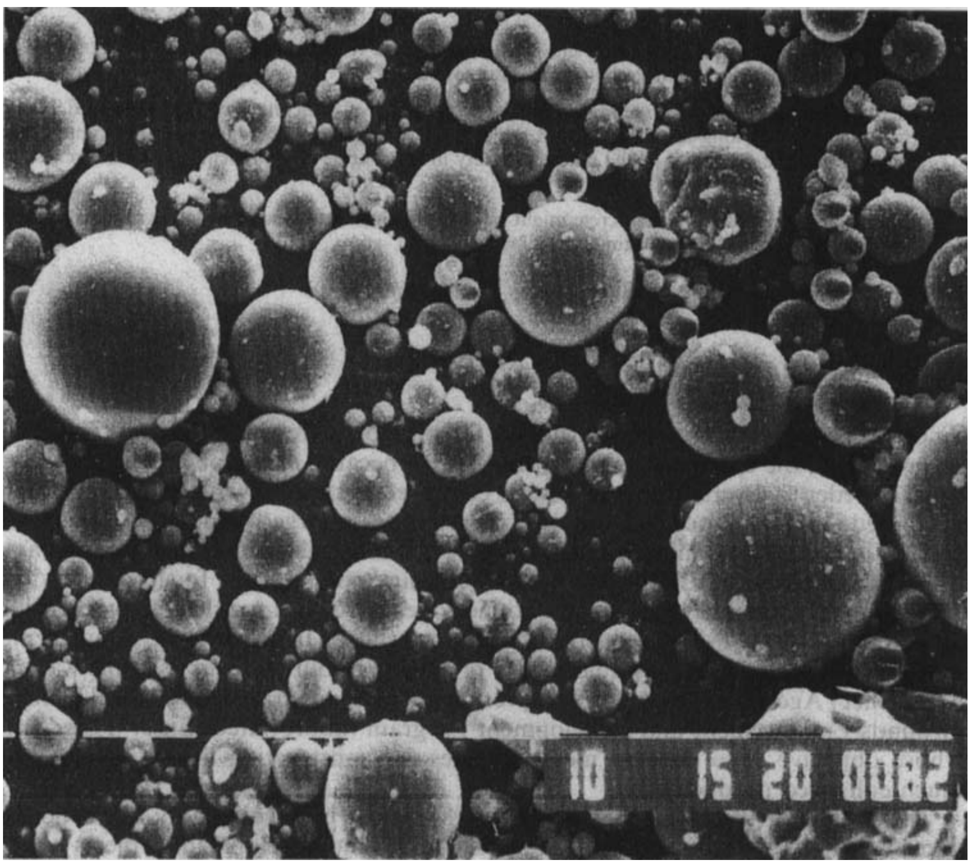

Figure 1 SEM Image of Fly Ash.

TEST METHODS

Materials Used

The chemical components and physical characteristics of two types of fly ash and Portland cement are shown in Table I. As activators, four mineral chlorides and sodium hydroxide, calcium hydroxide were used singly and in combination.

Mixing Ratio

Mixing ratios of the Ashcrete, plain mortar, and plain concrete used in the tests are shown in Table II. Also, in order to investigate the reactions of activators and their mixing behaviour with sea water, two kinds of artificial sea water were prepared and used in casting the Ashcrete.

Compressive-Strength Tests

Test pieces with dimensions 10 cm wide by 20 cm high were removed from the mould after aging for one day, and were cured immediately, both in the fresh tap water and the artificial sea water (ASTM D1141) at 20°C.

Microscopic Observation

Following the compressive strength tests, a sample was extracted from the test materials and was subjected to X-ray diffraction (XRD) analysis and scanning electron microscope (SEM) observation.

In the XRD analysis, the test material was crushed to a 200-mesh size and mixed with 5% by weight of zinc oxide, so that the diffraction intensity of zinc oxide may be used as the standard for quantitative analysis of reaction products.

Table I Chemical and Physical Properties of Fly Ash and Ordinary Portland Cement

Properties	Fly-Ash A (Domestic Coal)	Fly-Ash B (Australian Coal)	Ordinary Portland Cement
specific gravity	2.18	2.13	3.15
Blaine specific surface area (cm^2g^{-1})	2710	2450	3220
water content(%)	99	102	
relative compressive strength of mortar(%)			
Age 7 days	65	50	
Age 28 days	67	63	
Age 91 days	84	77	
loss on ignition(%)	1.0	3.0	0.6
SiO_2 (%)	51.1	62.2	21.8
Al_2O_3 (%)	29.3	27.3	5.4
Fe_2O_3 (%)	2.11	3.2	0
CaO (%)	9.6	0.8	64.0
SO_3 (%)	0.4	0	2.1
MgO (%)	2.1	0.5	2.0

Table II Mixing Proportions of Ashcrete, Ordinary Mortar and Ordinary Concrete

	W/ F+C (%)	C/ F+C (%)	Act/ F+C (%)	Cl/ F+C (%)	Unit Weight (kg m^{-3}) F	C	W	S	Act	G
Fly-Ash Concrete A:										
no activator	27	25	0	0	972	324	350	195	0	0
NaCl	27	23	1.46	0.89	972	324	330	193	18.9	0
KCl	27	25	1.86	0.89	974	323	351	193	24.2	0
$CaCl_2$	27	25	1.39	0.89	962	321	346	193	17.8	0
$MgCl_2.6H_2O$	27	23	2.54	0.89	960	320	343	192	32.3	0
artificial sea water I	27	25	–	0.34	971	324	350	193	–	0
artificial sea water II	27	25	–	0.54	971	324	350	193	–	0
Fly-Ash Concrete B:										
no activator	37	23	0	0	834	278	411	167	0	0
NaCl	37	25	1.46	0.19	830	277	410	166	16.2	0
KCl	37	23	1.86	0.89	833	278	411	167	21.7	0
$CaCl_2$	37	23	1.39	0.89	831	277	410	167	15.4	0
$MgCl_2.6H_2O$	37	23	2.54	0.89	830	277	409	166	28.1	0
artificial sea water I	37	23	–	0.73	834	278	411	167	–	0
artificial sea water II	37	23	–	0.73	834	278	411	167	–	0
Ordinary Mortar	–	–	–	–	0	434	273	1334	0	0
Ordinary Concrete	–	–	–	–	0	290	182	785	0	1077

Key:
F = fly ash, C = Portland cement, W = water, S = sand, G = gravel, Act = activator

TEST RESULTS

Compressive Strength Tests

a. Influence of various activators

Ashcrete test pieces mixed with various activators were prepared. They were cured in tap water and artificial sea water, before the compressive strength tests were performed. The compressive strength of Ashcrete showed wide variations depending on the anions in the activators. When mixed with activators with a single anion (NaCl, KCl), the compressive strength was remarkably high after 7 days of curing. However, after 182 days, the Ashcrete without an activator attained more than 85% of the strength of Ashcrete containing activators.

Figure 2 shows the compressive strength of Ashcrete which has been cured in artificial sea water. This was higher than the Ashcrete cured in fresh water even when no activator was used. After 182 days, however, all kinds of Ashcrete showed about the same compressive strength.

b. Influence of NaCl activator

As shown in Figure 3, the compressive strength increased with increase in the amount of NaCl added, until the NaCl mixture reached 1.5%. Further increase in NaCl, however, failed to induce any increase in compressive strength.

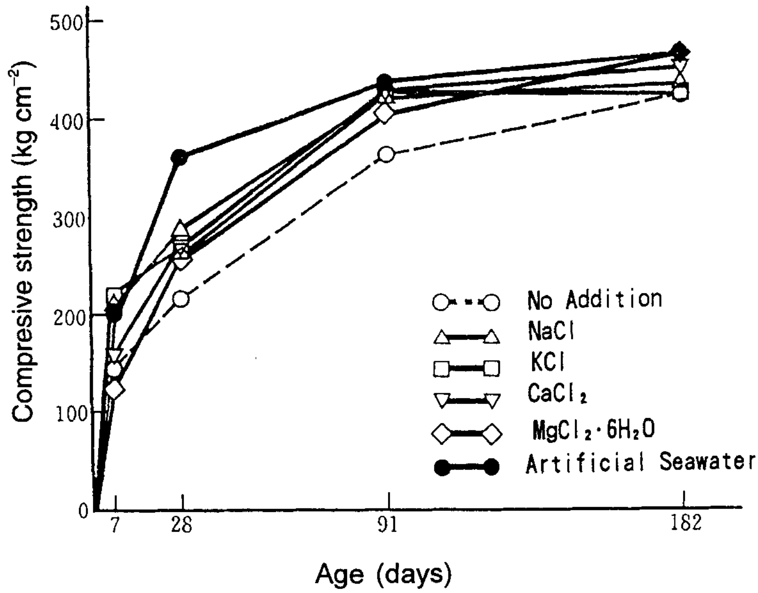

Figure 2 Compressive Strength of Ashcrete Incorporating Various Compounds.

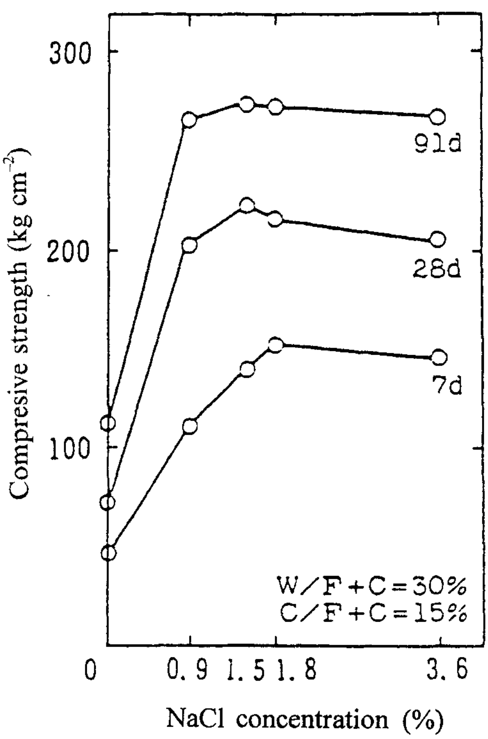

Figure 3 Relationship between Mix of NaCl and Compressive Strength.

The compressive strength of Ashcrete increased in proportion to increased amounts of NaCl and cement added in the Ashcrete. Addition of NaCl, in particular, caused a remarkable increase in compressive strength between the 7th through 28th days. For example, when the mixture ratio of NaCl was 1.46%, the 28th-day compressive strength was 400 kg cm^{-2}, about twice the strength of Ashcrete with no activators. This indicates that Ashcrete mixed with activators is sufficiently strong to be used in structures. Moreover, according to a two-way layout variance analysis, addition of NaCl accounted for 93% of the 28th-day compressive strength.

c. Influence of types of fly ash

Compressive strengths of Ashcrete, plain mortar, and plain concrete cured in the tap-water and artificial sea water are shown in Figure 4. Compressive strengths of plain mortar and plain concrete were lower when cured in artificial sea water than when cured in fresh tap-water. However, Ashcrete exhibited greater compressive strengths when cured in artificial sea water than when cured in tap-water, independent of the presence and types of activator, or the types of fly ash used. Ashcrete thus excels in resistance to sea water.

Microscopic Observation

In the hardening process of Ashcrete, initially silica and aluminium leach out on the surface of the fly ash particles, and as the reaction progresses, products resulting

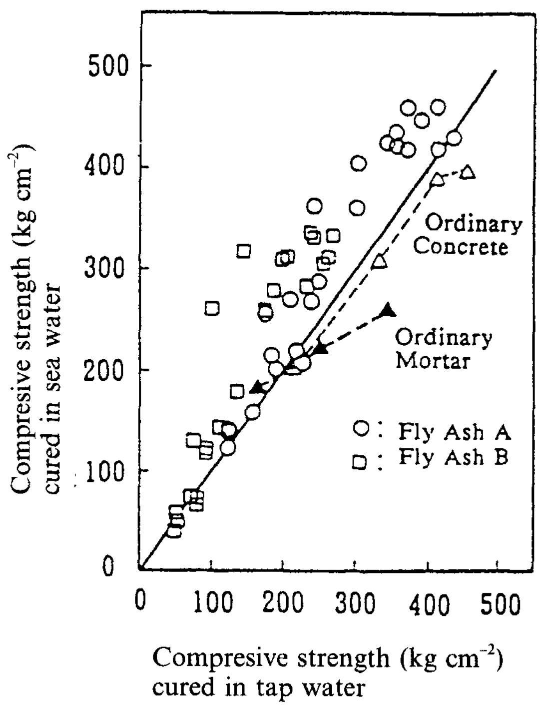

Figure 4 Compressive Strength Related to Types of Fly Ash and Curing Waters.

from this reaction fill the surface. In addition, as the reaction proceeds further, all the fly ash particles are linked together to form a continuous structure. According to the SEM observation, as shown in Figure 5, the Ashcrete containing NaCl, which exhibited high compressive strength on the 7th day of curing, had a smooth surface with almost no indication of active reaction. However, by the 91st day, as shown in Figure 6, many reaction products, appearing as cube-shaped and board-shaped particles have been created on the surface of the particles.

In the first stage of curing, strength development of Ashcrete is caused by reactions of the cement. During a long curing process, the reactions of the fly ash are added.

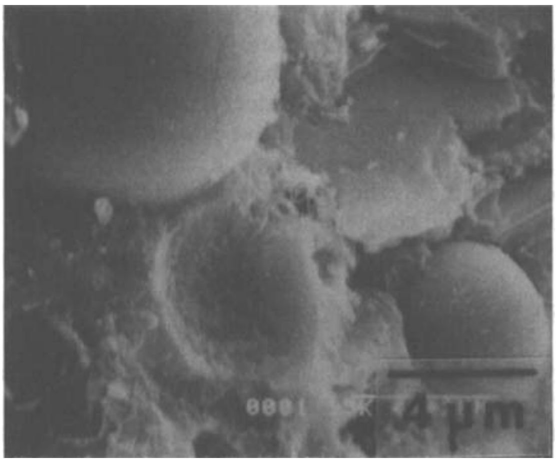

Figure 5 SEM Image of Ashcrete after 7 days, mixed with NaCl and cured in tap water.

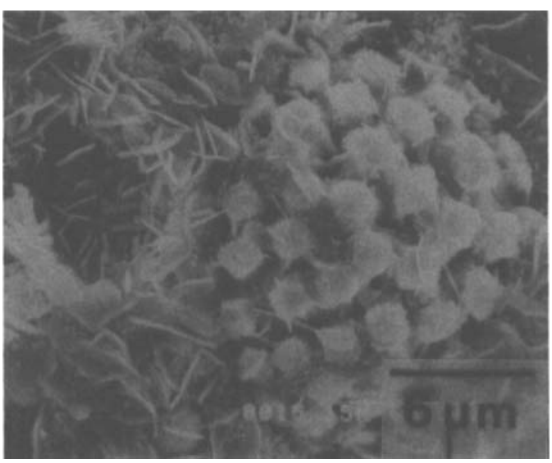

Figure 6 SEM Image of Ashcrete after 91 days, mixed with NaCl and cured in tap water.

Use as Fishing-Ground Material

Since 1980, artificial reefs made of Ashcrete have been constructed and installed at the number of experimental locations in Japan, mainly by electric power companies and construction companies. Comprehensive investigations of Ashcrete have been undertaken since 1986 as an official research programme of Marino-Forum 21 (an extra-departmental body that researches and effectively develops fishery resources along Japan's coastal regions) called 'Research Developments Concerning New Materials', and the results have substantiated its durability, safety, and practicality. Among these results the safety of Ashcrete was important for acceptance of the 'Ensei' Program. The Ashcrete passed all the safety requirements set forth by the Fishery Agency of the Japanese Government limiting the maximum contents for nine substances which are shown in Table III.

The results of those investigations have been compiled in 1988 by a panel of concrete experts into a 'Fly-Ash-Concrete Design and Construction Manual'. Following this, some additional studies have been performed to demonstrate the potential use of Ashcrete reefs as a subsidence-free structure on soft substrate by the Japanese Government. These studies have established successfully the feasibility of Ashcrete reefs in areas of soft substrate.

In 1990, for the first time in the world, Ashcrete has attained full legitimacy as a material eligible for public construction projects in Japan.

ARTIFICIAL SEA MOUNT CONCEPT

Fly ash used to be a waste, a nuisance to be disposed of by dumping in shallow waters at the expense of existing natural seaweed grounds which functioned as valuable marine habitat. However, now that the Ashcrete has attained fully fledged qualifications as a material for constructing facilities for fishing grounds, it is conceivable that it may even become useful for large scale construction projects such as artificial sea mounts for the purpose of generating upwelling, named 'Super Ridge'.

At the same time, in Japan Marino-Forum 21 is actively pursuing studies not only to induce fish aggregation, but also to enhance net production of biomass, thereby to preserve and increase living marine resources in coastal waters surrounding the nation. From this point of view, upwelling generating structures such as Super

Table III The safety standards of the Fishery Agency of the Japanese Government

Item	Standard (ppm)	Detectable Limit (ppm)
Cadmium and its compounds	< 0.01	0.01
Cyanogen	ND	0.2
Organic Phosphorus	ND	0.1
Lead and its compounds	< 0.1	0.1
Hexavalent Chromium	< 0.05	0.05
Arsenic and its compounds	< 0.05	0.05
Mercury and its compounds	< 0.0005	0.0005
Alkyl Mercury	ND	0.0005
PCB	ND	0.0005

ND = not detectable

Ridge have attracted attention. The upwelling carries deep sea water up towards the surface photic zone. In general, deep sea water is rich in nutrients, which can enhance phytoplankton growth. The large amount of phytoplankton so generated becomes the foundation of a food chain in the sea, leading ultimately to an increase in the fishing resources. In assisting in this visionary effort, Ashcrete may play an important role in the future.

The author has previously proposed the concept of Super Ridge, illustrated in Figure 7, as a means of enhancing marine resources but also to generate upwelling, thereby contributing to increased biomass production. This concept calls for the use of Ashcrete for building large-scale marine structures such as Super Ridge rivalling natural reefs in size and scope.

A 1 million-kW coal-powered generating station, operated for 30 years, will produce coal ash equalling 10 million tonnes. Supposing that this fly ash is used to produce Ashcrete, and the whole amount of this Ashcrete is used in the construction of Super Ridge at a depth of 100 m, the result will be 40 Super Ridges each 30 m high, 120 m wide at the base, 300 m long at the base. If placed linearly at intervals of 150 m, the entire assembly will form a gigantic series of underwater mountain ridges stretched out for approximately 18 km in length. These Super Ridges could generate 15,000 m^3s^{-1} upwelling, bringing 9,000 t-atN yr^{-1} nutrients to the photic zone. This nutrient increase could theoretically produce 8,000 tonnes of fish a year after 30 years.

The use of Ashcrete for this type of project means not only the initiation of a biomass-producing upwelling region in the offshore waters, but also preservation

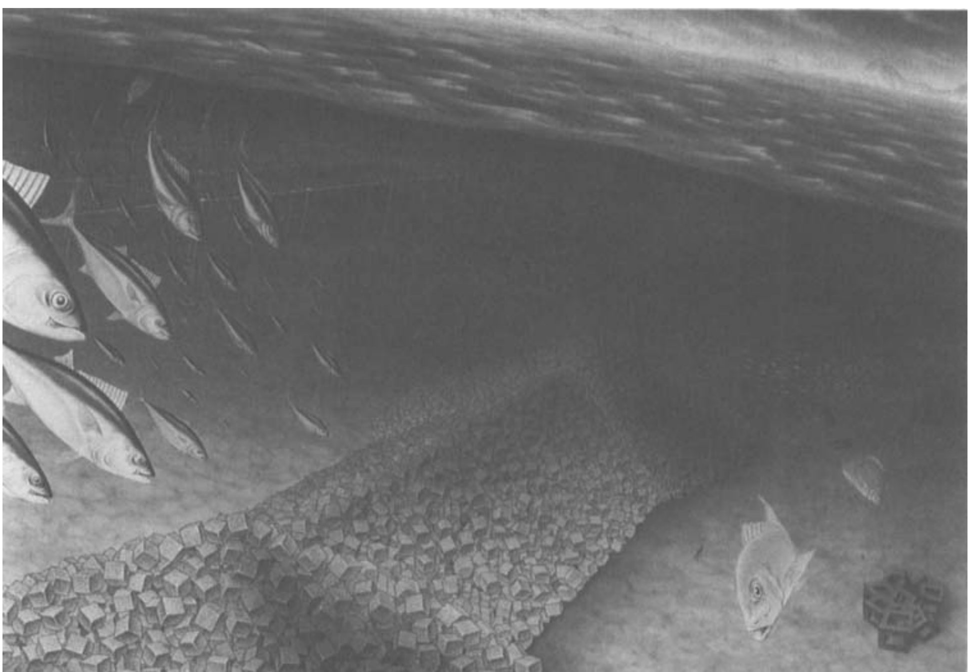

Figure 7 Conceptual Drawing of Artificial Sea Mounts named Super Ridge. (See Colour Plate I at the back of this issue)

of coastal habitats because future loss of inshore areas due to the disposal of fly ash as a waste product would cease.

CONCLUSION

This report has introduced the results of experimental tests on the characteristics of Ashcrete with special reference to compressive strength, resistance to sea water, and safety for marine life, along with examples for promising applications.

These tests have demonstrated that the compressive strength of Ashcrete is not only a function of curing conditions but also of the types and amounts of various chemical activators which are mixed into the Ashcrete. More specifically, it was found that the addition of an appropriate activator such as NaCl curing in artificial sea water will greatly enhance both initial and long-term strength. The resistance of Ashcrete to sea water is judged adequate in light of its compressive strength characteristics and microstructure.

Furthermore, it has been learned that artificial reefs constructed of Ashcrete are safe for organisms, favourable for attachment by sessile life, and can induce excellent aggregation of fish.

It therefore appears that Ashcrete might well be used in constructing large-scale sea mounts for the purpose of generating upwelling.

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