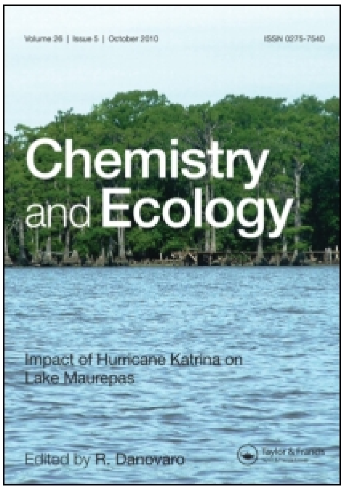

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EXPERIENCES OF COAL ASH ARTIFICIAL REEFS IN TAIWAN

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A feasibility study for using fly-ash from Taiwan coal-fired power stations for artificial reef production was started in 1983. Various mixtures of fly ash stabilized with lime, cement, or industrial wastes and formed into blocks were tested in the laboratory. The results showed that the development of compressive strength of those blocks immersed in the sea water was much better than those exposed in the air. Heavy metal (Cd, Cr, Cu, Ni, Pb, Zn) content of the blocks has been monitored routinely to determine the leaching rates. The result indicates that solidification of fly-ash could indeed immobilize heavy metals better than the original fly ash. From March 1984 to February 1987, 3,682 coal ash stabilized blocks with total weight of 300 tons were designed, fabricated and installed at both Hsin-ta, south western coast, and Kuei-hou, northern coast of Taiwan, for field trials. After four years' underwater observations on 100 cubic blocks at Wan-Li, northern Taiwan, it was shown that the physical integrity of the ash reef blocks had been maintained. The compressive strength and durability was better than the concrete artificial reefs nearby. The ash reefs could also attract fishes and the colonization by benthic organisms was similar to that on concrete reefs. Eighty-eight species of fishes were observed, of which 27 were commercially important, comprising more than 80% of the total biomass. These results demonstrate a potential use for stabilized coal ash as artificial reefs to replace traditionally used concrete reefs to protect and enhance the coastal fishery resources in Taiwan in the future.

KEY WORDS: Fly-ash reef, artificial reef, colonization, mariculture, fish community

INTRODUCTION

The use of artificial reefs to change the marine environment by providing more shelters for marine organisms and to enhance the fishery resources has become an important issue in the world. Although scrap materials such as sunken boats, junk cars, or used tyres could be used as the reefs, concrete is still the most popular material was used to construct artificial reefs in many countries during the past two decades, especially in Japan and Taiwan. Since 1973, the Taiwan government has built a large number of reefs to improve or protect the fishery resources and more than 45,000 reef blocks have been installed at fifty different reef sites along the coast waters of sixteen counties. The effectiveness of some of these reef sites was evaluated and reported positively. However, some features detracted from the ineffectiveness such as, installations were too scattered to attract fish, or reefs at several sites were half buried or buried by sand following typhoons (Shao, 1988).

One way to improve this massive artificial reef project in the future would be to reduce the cost involved in using concrete. The use of coal fired power station wastes (Pulverized Fuel Ash, PFA) for reef construction would meet this requirement as well as solving the coal-waste problem from power plants. Before 1985 coal ash production in Taiwan was less than 1 million tonnes per year, most of which was used in land reclamation or dumped in the ocean. Currently approximately 1.3 million tonnes of fly ash are produced from five coal fired power plants each year. Up to 50% of this is utilised by the concrete and cement industry for road pavement and building construction, and the remainder is used to reclaim the foreshore in ash ponds beside the coastal power plants.

The earliest studies of using fly-ash to construct reefs were made in 1975 (Woodhead *et al.*, 1982). Following a series of studies at Long Island Sound, Woodhead and Jacobson (1985) concluded that the cement stabilized coal waste was compatible with the marine environment. A similar experimental structure was deployed in Poole Bay, off the central south coast of England in 1989. Collins *et al.* (1990a, 1990b, 1992) also demonstrated its physical integrity, increasing compressive strength, low heavy metal leaching, and rapid colonization by reef fishes. Other parallel studies which have been carried out in temperate waters were in Italy (Sampaolo and Relini, 1991) and in Japan (Suzuki, 1994). Taiwan is the closest to tropical waters and the southern most country to have carried out such studies.

This paper summarizes our experimental results from a series of the feasibility studies for using coal ash as reef material during January 1983 to November 1990. The whole procedure can be divided into three phases:

1. Laboratory tests of a physical, mechanical and chemical nature in order to find the proper formula for constructing the ash reefs (Kuo *et al.*, 1985).
2. Construction of different types of reef models and their installation in coastal waters to monitor their short term effectiveness (Chen *et al.*, 1985, 1986, 1987).
3. Long term evaluation of ash reef effectiveness in northern Taiwan with an emphasis on the fish community (Shao and Chen, 1992).

MATERIAL AND METHODS

Physical-mechanical Tests

Test materials include PFA from both Sen-ao and Hsin-ta Power Plants, waste carbide from an ethylene producing factory, lime, and Portland cement. The physical and chemical properties of the fly ash and waste carbide are shown in Table I. The trace element content of the fly ashes is listed in Table II. The calcium content of fly ash is low in comparison to the waste carbide which contains calcium hydroxide.

Various types of mixture of fly ash with other stabilizers were manufactured into blocks in the laboratory by adding an appropriate amount of water. Each block measured 5 cm × 5 cm × 5 cm. They were allowed to cure indoors in a saturated water atmosphere for 3 months. Compressive strength was measured after 30 and 90 days. Most test blocks were kept in three different types of environment: immersion in water, outdoor exposure, and indoor exposure. Their compressive strength was measured periodically over one year.

Chemical Studies

The leaching of heavy metal ions from different formulations of stabilized ash blocks was studied by immersing them in deionized water or sea water. Blocks after 3

Table I Physical and chemical properties of the fly ash (FA) and carbide waste used in the study

	FA (Sen-ao)	FA (Hsin-da)	Waste carbide
General appearance	powders	powders	slurry
Original water content (%)	0.53	0.54	46~62
Chemical composition (dry base)			
Loss on Ignition at 850°C (%)	7.50	2.95	22.48
SiO_2 (%)	62.30	57.00	1.83
Al_2O_3 (%)	21.64	19.78	0.08
Fe_2O_3 (%)	3.00	9.30	0.50
CaO (%)	0.45	4.10	76.60
MgO (%)	0.40	1.08	0.10
K_2O (%)	1.07	2.25	0.04
Na_2O (%)	0.27	0.43	0.04
S (%)	0.04	0.11	0.24
True density (g/cm^3)	2.06	2.24	–
Fineness (% retained on 325 mesh)	13.80	17.00	–
Activity Index (% cement 28 days)	90.34	69.94	–

Table II Trace elements in fly ash ($\mu g\ g^{-1}$)

	FA (Sen-ao)	FA (Hsin-ta)
Ag	2	5
As	2.6	20
B	280	860
Cd	<5	5
Co	16	39
Cr	83	156
Cu	27	144
Hg	<1	1
Mn	766	483
Mo	15	35
Ni	47	166
Pb	43	81
Se	87	50
U	19	18
V	43	59
Zn	80	413

months curing, as described in previous section, were used as the test material. Original fly ash from Sen-ao and Hsin-ta Power Plant were used as the controls. Samples of about 200 g were taken from each block and dried in an oven at 105 ± 5°C to constant weight. These samples were immersed in 600 ml deionized water or natural sea water in 1000 ml beakers and maintained with continual agitation at a water temperature of 37 ± 2°C. The water samples were replaced and analyzed every two weeks. The concentrations of cadmium, chromium, copper, nickel, lead and zinc were measured in an atomic absorbtion spectrometer. Deionised water samples were analyzed directly, but sea water samples were treated initially with NADDC and AAPDC chelate to eliminate the matrix interference.

Reef Construction

Based on the results of preliminary experiments on 5 cm × 5 cm × 5 cm blocks, eight kinds of mixtures of ash blocks (types A–H in Table IV) were manufactured into small, simple, four-hole blocks (30 cm × 30 cm × 30 cm). A total of 160 blocks were installed in the Hsin-ta harbour in June 1984 (Table III). Ten further block compositions (types I–R, Table IV) were made in situ on the beach of Hsin-ta and then installed at Mi-tou. The characteristics of these one-hole small rectangular blocks include:

a) use of sea sand instead of river sand to lower the cost;

b) little use of waste carbide since the sources of this material were too far away;

Table III Details of experimental coal ash reefs in Taiwan

Year	Reef Type	Number	Sites	Depth
1984	Four-hole small simple block	160	Hsin-ta harbour	1~3 m
	One-hole small simple block	2,340	Offshore of Mi-tou	15 m
1985	Two-hole small simple block	800	Hsin-ta	15 m
		200	Wan-li	12 m
	Cylindrical	1	Hsin-ta	15 m
	Turtle-shell	2	Hsin-ta	15 m
1986	Two-hole small simple block	200	Wan-li	10 m
	Cylindrical block	15	Hsin-ta	15 m
	Cubic block	100	Wan-li	10 m

Table IV Composition of the different types of fly ash blocks

	Percentage composition (by wt)							
Types	Fly-ash	Waste carbide	Lime	Cement	Sand	Gravel	Other	Water/Dry material
A	70	30	–	–	–	–	–	0.35
B	70	30	–	–	–	–	–	0.45
C	68	30	–	2	–	–	–	0.45
D	58	40	–	2	–	–	–	0.60
E	80	–	20	–	–	–	–	0.35
F	–	–	–	12	35	53	–	0.50
G	90	–	–	10	–	–	–	0.35
H	50	30	–	–	–	–	(Oyster Shell) 20	0.45
I	95	–	–	–	5	–	–	
J	63	35	–	2	–	–	–	0.5
K	70	30	–	–	–	–	–	|
L	80	–	20	–	–	–	–	0.7
M	60	–	10	10	20	–	–	
N	60	–	–	10	30	–	–	
O	60	–	–	8	30	–	(paint) 2	
P	60	–	10	15	15	–	–	0.42
Q	60	–	15	10	15	–	–	0.42
R	70	–	10	10	10	–	–	0.42

c) use of both lime and cement together *in situ* because their commercial prices were similar and cement can improve the compressive strength in the early development stage, while lime is useful for its long term development.

After comparing the compressive strength of test blocks, type P was selected as the best formula for construction of massive ash reefs. Table III lists the different kinds of reef types including two-hole small rectangular blocks, giant cylindrical or turtle shell blocks, or cubic blocks (Figure 1) and their numbers, casting sites, and water depth from 1984 to 1986. Only the 100 cubic blocks (1.5 m × 1.5 m × 1.5 m) which were installed in September 30, 1986 at the Kuei-ho, Wan-li, northern coast of Taiwan were used for long term evaluation. The formula of this type P is 176 kgm^{-3} PFA, 210kg cement (F/C + F = 0.46), 685 kgm^{-3} sand, 1008 kgm^{-3} gravel and water (W/C + F = 0.56). The compressive strength after 28 days was 227 kg

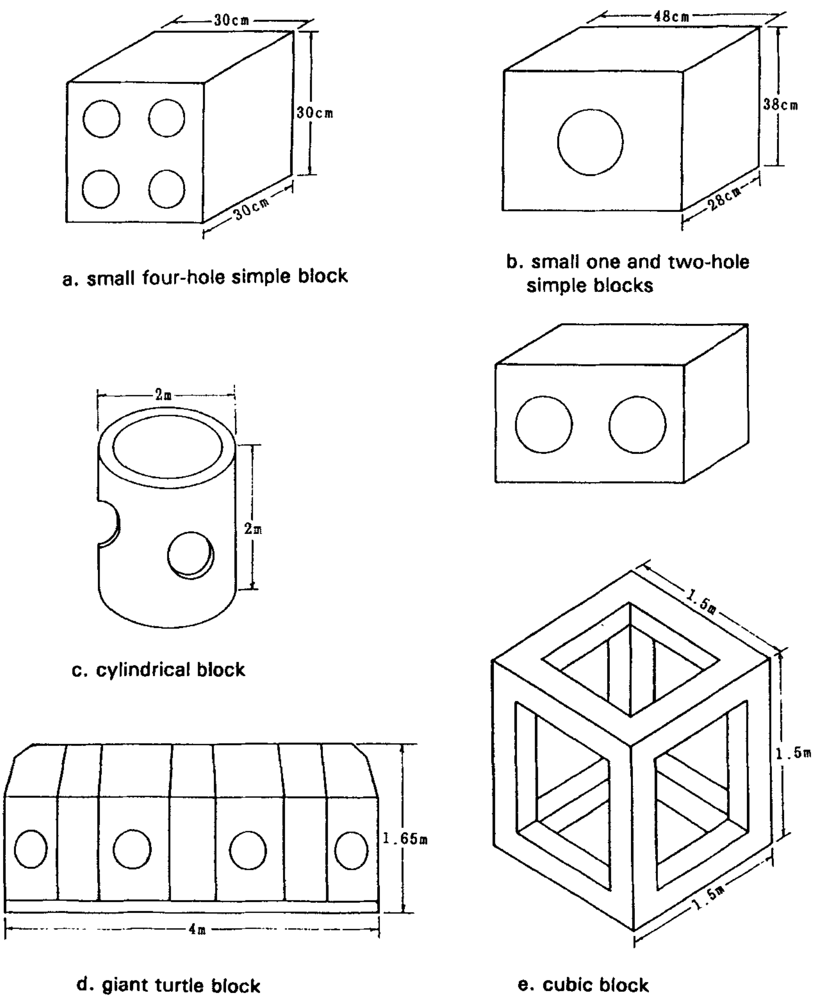

Figure 1 Types of coal ash artificial reef units used in Taiwan.

cm^{-2} (3223 psi) which meets the general requirement of constructing artificial reefs in Taiwan (2500 psi). In total, 3,664 small, simple blocks (40–45 kg each), 16 cylindrical blocks (6.5 tons each), 2 turtle shell blocks (17.8 ton each), and 100 cubic blocks were made during 1984–1986 and installed both at Hsin-ta, Kaohsiung County (22°51.07′N; 120°07.09′E) and at Kuei-ho, Wan-li, Taipei County (25°11.54′N; 121°40.8′E) (Figure 2).

Biological Studies

After the reefs were installed, underwater surveys were used to record the structural integrity, durability, and stability of the reef blocks as well as the colonization of sessile or benthic organisms and fish assemblages. However, due to high water turbidity, the difficulties in relocating the reef site and the burying of some reefs by

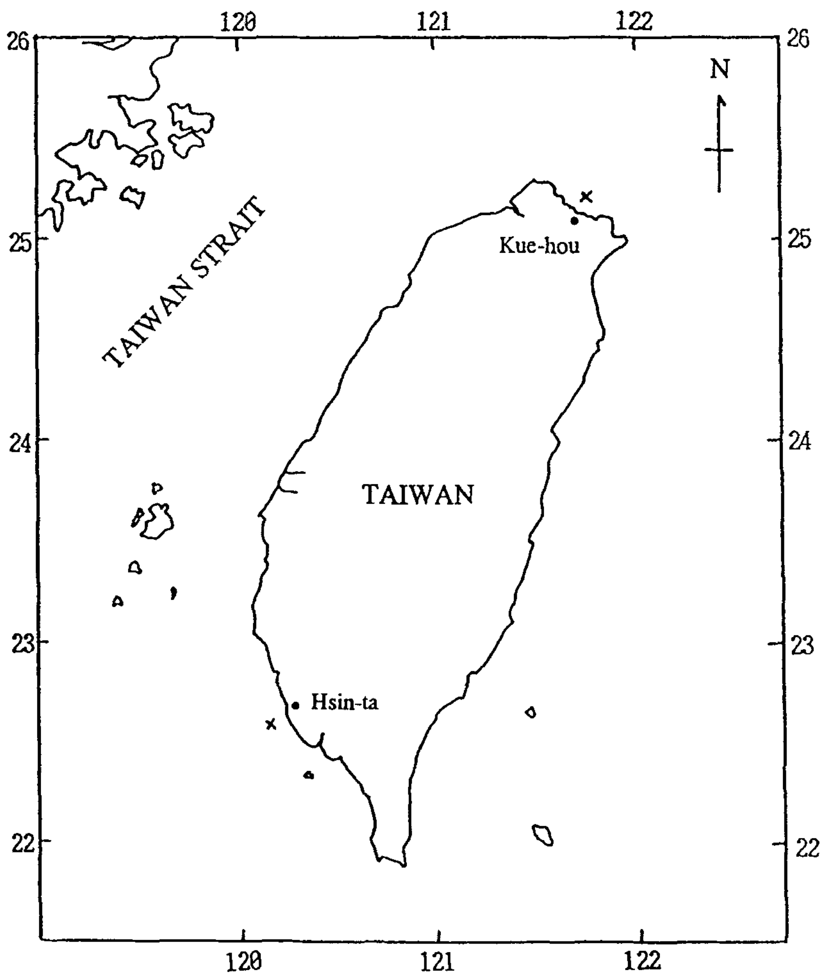

Figure 2 Location of the coal ash artificial reefs in Taiwan.

sand, direct underwater observation of reefs at Hsin-ta and for the 200 two-hole small blocks at Wan-li was limited. Nevertheless, by using a fish finder, tagging of sea bream, and bottom long-lining on the Hsin-ta reefs, Chen *et al.* (1985–1987) obtained more than 20 commercial fish species and reported that the catch per unit effort was significantly higher at the reef sites than non-reef sites.

The present paper only briefly summarizes our long term monitoring results on the 100 cubic blocks which were installed in September 1986. A total of 14 surveys were made during September 1986 to November 1990. Samples of sessile organisms were collected for identification in each dive. Fish assemblages were recorded, noting body size range and the number of individuals of each species.

RESULTS

Physical-mechanical Determinations

After 15 months curing period in the laboratory, the compressive strength of different mixtures are compared in Figure 3. Apparently the greatest compressive strength was shown by blocks submerged in sea water, followed by those exposed outdoors on land, whilst those kept indoors were the weakest. Fly ash stabilised with waste carbide or lime in the ratio of 4:1–1:1 by weight followed by 90 days curing in sea water, has a compressive strength sufficient to satisfy the minimum requirement of the Taiwan EPA for ocean deployment (100 kg cm^{-2}). Figure 4 demonstrates the increase in compressive strength of various types of mixture with time. Addition of some cement in the test mixtures will speed up the compressive strength of the blocks at an early stage. Thus, no matter how the blocks were constructed, moulding under pressure or pouring, the final compressive strengths are similar.

When comparing the compressive strength of different composition mixtures, it was shown (Figure 5) that formula P (fly ash 0.6, lime 0.1, cement 0.15, sea sand 0.15, water/dry material = 0.42) and Q (fly ash 0.6, lime 0.15, cement 0.1, sea sand 0.15, water/dry material = 0.42) were the two best types. Their compressive strength could exceed 180 kg cm^{-2} (2556 psi) after 28 days of curing.

The physical integrity, including and surface hardness, of the 100 cubic blocks installed off the northern coast seemed to be good. There was no evidence of any significant movement of blocks after deployment. Only sand scouring was evident on some reefs and some destruction of broken corners due to collision during initial installation. The surface of the blocks showed no significant porosity throughout the experimental period. Thus, the structural integrity of fly ash reef blocks was better than that of the plain concrete blocks.

Chemical Determinations

Heavy metal concentrations (6 elements × 4 replicates) from fly ash and block leachates are shown in Table V. Comparison of this Table with the original heavy metal content of fly ash in Table II indicates that only in the case of chromium was leaching greater than from the original ash. The leaching rates of the other five elements were very low. Although no regular trends or profiles of metal concentration could be observed from Table V, solidification of fly ash can immobilize the trace elements in the block and decrease their leaching rate.

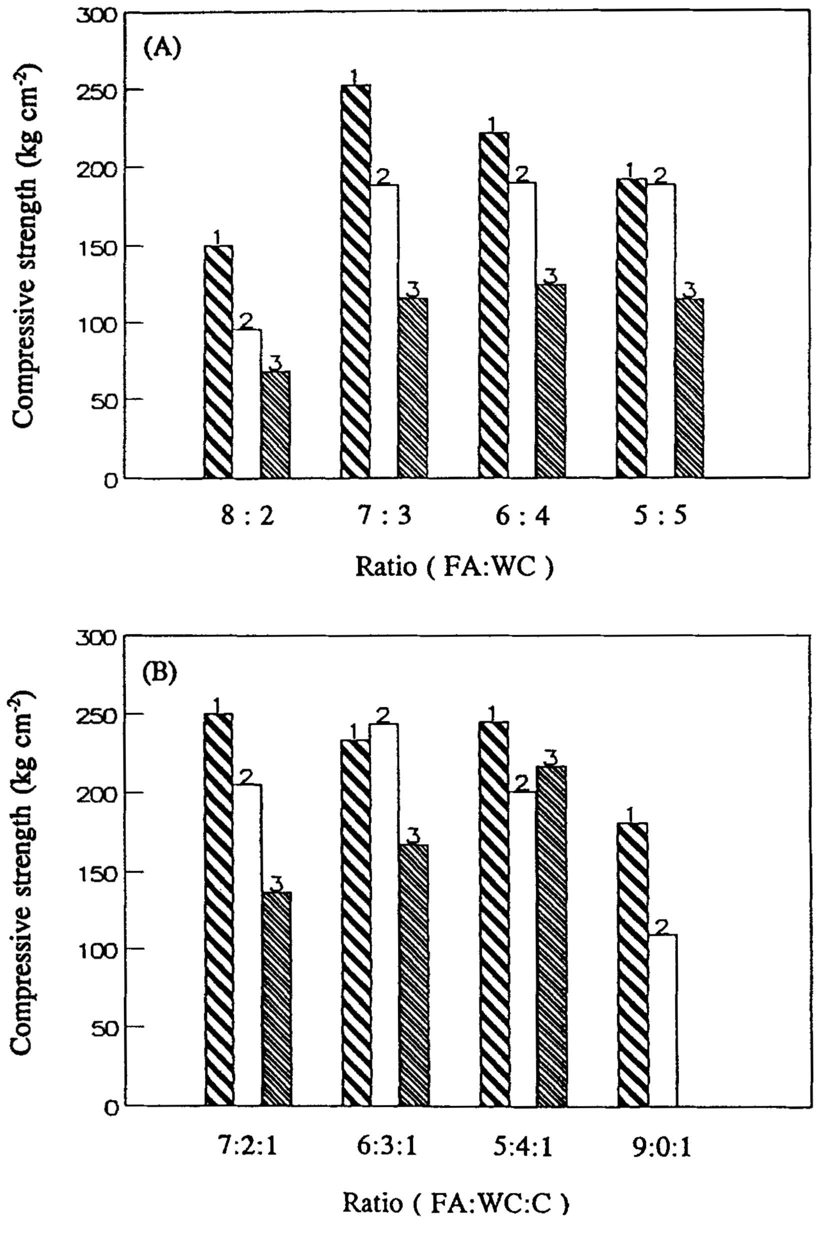

Figure 3 Comparison of the compressive strength of four different fly ash (FA), carbide waste (WC) and cement (C) mixtures formed by moulding (A) or pouring (B) after 15 months using three curing methods; sea water (1), outdoor exposure (2) and indoor exposure (3).

Biological Studies

After one month of installation at Kuei-ho, algae were the first visible organisms found on the block surfaces. Top shells (*Tectus* sp.) appeared subsequently. One

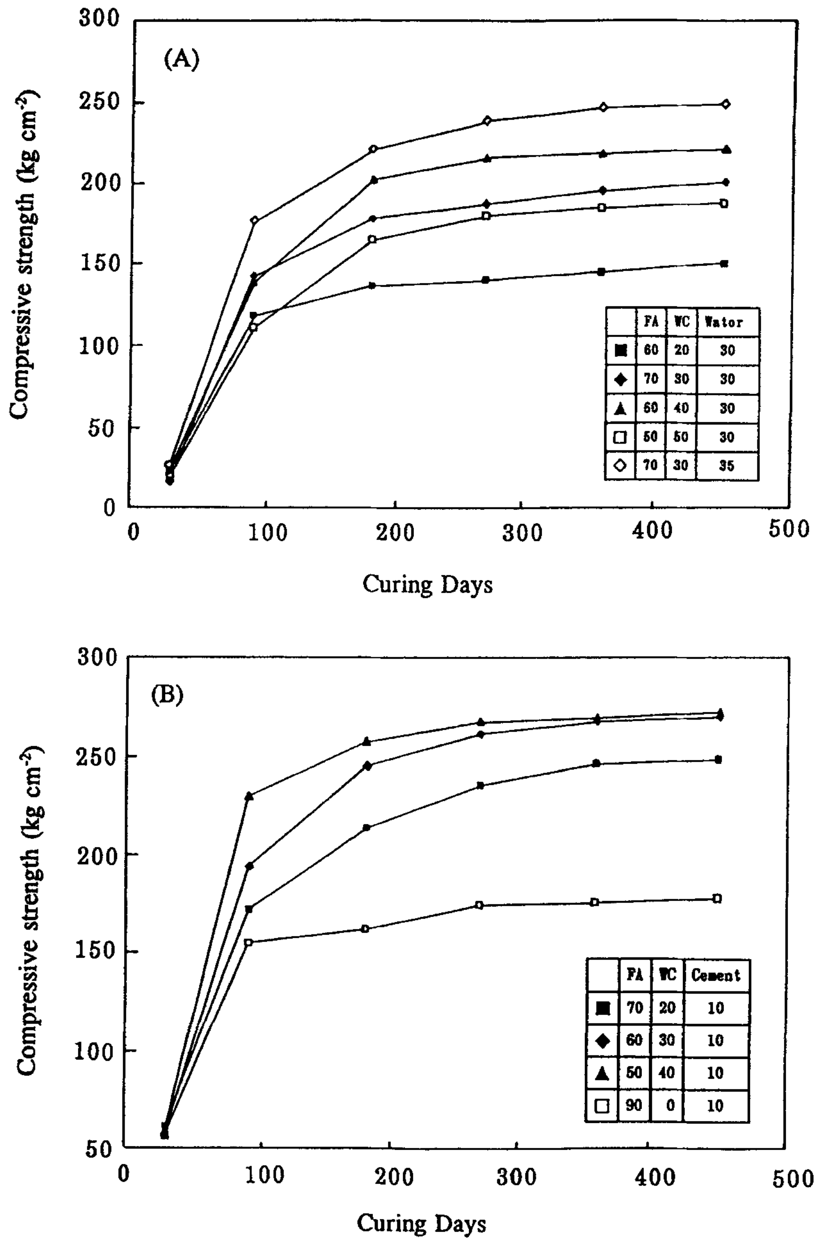

Figure 4 Compressive strength of various fly ash (FA) and carbide waste (WC) mixtures formed by moulding (A) or pouring (B) related to time curing in sea water.

year later, round lichenous bryozoans grew densely on the surface and the number of bivalves, gastropods and barnacles increased, but mobile benthic invertebrates were rare in the first year. After 18 months, bush-like hydroids (*Macrorhychia* sp.) grew on both the dark and lateral sides of the reefs. Calcareous algae, sponges, sea

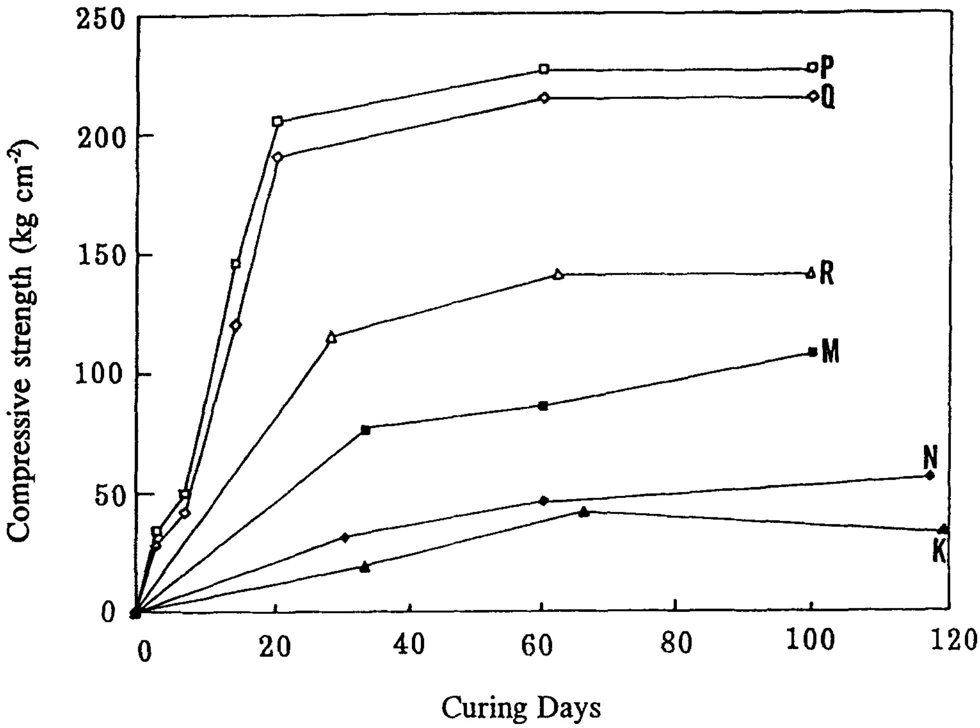

Figure 5 Compressive strength of various fly ash mixtures (listed in Table IV) related to curing time in sea water.

squirts became the dominant epifauna. Many small molluscs, hermit-crabs, and sea urchins moved into this epifaunal layer. Two years later, the number of species of encrusting organisms increased together with the thickness of encrusting layer. Corals, sea slugs with egg masses, crinoids, and many small crustaceans were found from the sample specimens collected from the reef surfaces after three years.

A total number of 30 families, 53 genera, and 88 species of fishes were observed from 14 surveys (Table VI). Though only 27 of these species are of commercial value, these represent over 80% of the total biomass. The most important commercial species which schooled around the reefs were fusilier (*Pterocaesio diagramma*), barracuda (*Sphyraena flavicauda*), three-lined grunts (*Parapristipoma trilineatum*), surgeonfishes (*Prionurus scalprus*), and scads (*Seriola* sp.). Barracuda and three-line grunts were seasonal migrants which usually appeared from May to August and from October to November respectively. Many juveniles or young of fusilier or grunts were found around the reefs. This implies that the ash reef also functioned as a nursery ground in the same way as the concrete reefs nearby.

Other fishes frequently wandering near the base of the reef include snappers (*Lutjanus vitta*), filefishes (*Thamnaconus modestus*), grunts (*Plectrorhynchus* spp.), morwongs (*Goniistius* spp.) and wrasses (*Choreodon azurio*). In addition, *Oplegnathus punctatus*, *Cephalopholis* spp., *Sebastiscus marmoratus*, *Lethrinus* spp., or *Acanthurus* spp. were seen occasionally. Coral reef fishes such as the damselfishes; *Chromis notatus*, *Chromis fumea*, or *Neopomacentrus taeniurus* were the three most abundant

Table V Heavy metal concentrations in leachates from fly ash and different compositions of stabilised coal ash block. (FA(1 or 2) – flyash, WC – waste carbide, L – lime, C – Portland cement, ND – not detected)

Solvent	Conc. ($\mu g l^{-1}$)	No. of test	Sen-ao (FA1)	Hsin-ta (FA2)	FA1 70 + WC 30	FA1 80 + L 20	FA1 68 + WC 30 + C 2	FA2 90 + C 10
deionized water	Cd	1	0.04	ND	ND	ND	ND	ND
		2	ND	ND	ND	ND	ND	ND
		3	ND	ND	ND	ND	ND	ND
		4	ND	ND	ND	ND	ND	ND
	Cr (total)	1	33.7	1715.0	1.1	4.8	1.2	181.3
		2	4.1	638.8	2.4	2.1	ND	143.8
		3	7.4	351.8	0.5	1.6	ND	38.8
		4	1.0	241.1	ND	0.6	ND	17.3
	Cu	1	ND	2.3	10.2	ND	2.1	5.5
		2	ND	ND	0.9	ND	ND	ND
		3	ND	ND	ND	ND	ND	ND
		4	ND	ND	0.6	ND	ND	1.8
	Ni	1	1.5	6.1	0	0.5	4.7	3.0
		2	3.5	0.4	0	ND	0.04	ND
		3	2.0	ND	0	ND	ND	ND
		4	ND	ND	0	ND	ND	2.2
	Pb	1	0.3	3.4	0.7	0.4	0.4	0.2
		2	ND	ND	ND	ND	ND	ND
		3	2.3	7.8	0.4	0.3	ND	ND
		4	1.4	0.9	ND	ND	ND	ND
	Zn	1	0.7	ND	0.3	1.6	4.3	ND
		2	ND	ND	ND	ND	ND	ND
		3	ND	ND	ND	ND	ND	ND
		4	ND	ND	ND	ND	ND	ND
sea water	Cd	1	9.8	ND	ND	ND	ND	ND
		2	3.0	0.5	ND	ND	0.6	0.2
		3	2.0	0.6	ND	ND	0.1	ND
		4	2.5	0.6	0.2	0.1	0.1	0.2
	Cr (total)	1	701.4	1483.6	ND	ND	ND	191.3
		2	45.4	679.5	3.7	5.0	5.8	75.9
		3	3.8	35.9	0.1	0.6	0.3	17.4
		4	12.0	29.1	ND	ND	ND	5.2
	Cu	1	0.9	0.9	9.3	1.7	1.7	5.1
		2	0.9	0.9	7.7	ND	1.7	3.4
		3	ND	ND	5.8	ND	ND	2.9
		4	0.5	2.9	5.3	0.4	ND	4.4
	Ni	1	52.8	0.8	1.6	0.9	ND	0.1
		2	21.7	1.7	3.8	ND	0.6	ND
		3	29.9	0.2	0.6	ND	ND	0.3
		4	17.1	6.9	0.6	ND	ND	1.2
	Pb	1	ND	0.1	0.1	0.1	ND	0.2
		2	ND	ND	ND	ND	ND	0.8
		3	ND	0.1	ND	0.7	1.8	0.4
		4	0.3	0.8	ND	2.4	ND	1.4
	Zn	1	ND	49.9	237.7	ND	209.8	ND
		2	2.8	ND	ND	ND	ND	2.2
		3	ND	ND	ND	ND	ND	ND
		4	41.2	82.6	ND	11.1	ND	49.6

Table VI A list of fish species, their relative abundance and number of times observed (out of 14 surveys) recorded from fly ash reefs located at Kuei-ho between Nov. 1986 to Nov. 1990. (key; R – rare, O – occasional, C – common, A – abundant, # – commercial species, * – dominant species)

Family	Species	Abundance	Frequency
Aulostomidae	*Aulostomus chinens*	R	1
Sphyraenidae	# *Sphyraena flavicauda*	C	4
	#* *S.*sp.	C	4
Chaetodontidae	*Chaetodon octofasciatus*	R	3
	C. auripes	O	12
	C. kleinii	R	1
	Coradion altivelis	R	2
	Heniochus acuminatus	R	1
Pomacanthidae	*Pomacanthus semicirculatus*	R	3
	Chaetodontoplus septentrionalis	C	11
Pomacentridae	* *Chromis notatus*	A	14
	* *C. fumeus*	A	11
	C. cinerascens	R	3
	C. ovatiformis	R	2
	C. sp.	R	3
	Pomacentrus coelestis	C	11
	Stegastes apicalis	R	1
	S. jenkensis (fasciolatus)	C	11
	Abudefduf septemfasciatus	O	2
	A. coelestinus	O	1
	* *Neopomacentrus taeniurus*	C	3
Labriidae	# *Choerodon azurio*	O	11
	Pseudolabrus japonicus	O	10
	Pseudocoris yamashiroi	O	3
	Halichoeres poecilopterus	O	5
	H. melanochir	C	11
	H. tenuispinnis	R	2
	H. sp1.	R	2
	H. sp2.	R	1
	Bodianus diana	R	1
	B. axillaris	R	1
	Pteragogus fagellifera	O	2
	Labroides dimidiatus	O	11
	Stethojulis bandanesis	O	3
	S. strigiventus	R	2
	S. trilineatus	O	3
	S. interrupta	O	3
	Suezichthys gracilis	R	1
	Thalassoma lunare	O	7
Carangidae	# *Seriola dummerili*	O	1
Lutjanidae	# *Lutjanus monostigma*	C	6
	#* *L. russellii*	C	3
	# *L. lutjanus*	O	1
	#* *L. vitatus*	O	4

species present in large schools in midwater layers. Species of wrasse (Labridae), butterflyfish (Chaetodontidae), angelfish (Pomacanthidae), and cardinalfish (Apogonidae) used the blocks as feeding grounds and shelters. The fish assemblages included herbivores, zooplankton feeders, carnivores, and omnivores, indicating that the reef population has matured and stabilized.

In general, fish assemblages seem to be more abundant in summer than in winter but further work is needed since most species were rare or occasional visitors. The

Table VI Continued

Family	Species	Abundance	Frequency
Caesionidae	# * *Pterocaesio diagramma*	A	12
Apogonidae	*Apogon nitidus*	A	3
	A. cyanosoma	C	2
	A. doederleinii	C	6
Serranidae	# *Cephalopholis boeneck*	O	11
	# *C. argus*	R	2
	# *Epinephelus sp.*	R	2
Scorpaenidae	*Scorpaenopsis cirrhosa*	O	4
	S. sp.	R	1
	# *Sebastiscus marmoratus*	R	1
	Dendrochirus bellus	R	2
	D. zebra	O	3
Mullidae	# *Parupeneus trifasciatus*	R	1
	# *P. pleurotaenia*	O	3
	# *P. indicus*	O	1
	# *Upeneus tragula*	O	1
Monoacanthidae	# * *Thamnacomus modestus*	C	13
	Stephanolepis cirrhifer	R	1
Scaridae	# *Scarus ghobban*	R	5
	# *S. rubroviolaceus*	R	2
	S. sp.	R	2
Zanclidae	*Zanclus cornutus*	O	3
Mugiloididae	*Parapercis clathrata*	R	4
	P. xanthozona	R	1
Holocentridae	*Sargocentron rubrum*	R	4
	S. caudimaculatum	R	1
Blenniidae	*Petroscirtes breviceps*	R	1
	Scartella cristata	O	1
Gobiidae	*Eviote abax*	O	2
	Istigobius decoratus	O	2
Cheilodactylidae	# *Goniistius zonatus*	O	8
	# *G. quadricornis*	R	2
Lethrinidae	# *Lethrinus* sp.	O	1
Haemulidae	# * *Parapristipoma trilieatum*	A	1
	# *Plectorhynchus pictus*	O	9
Scorpididae	*Microcanthus strigatus*	O	7
Oplegnathidae	# *Oplegnathus punctatus*	R	1
Acanthuridae	*Acanthurus dussumieri*	O	4
	A. sp.	O	2
	# *Prionurus scalprus*	R	4
Grammistidae	*Diploprion bifasciatus*	O	7
Balistidae	*Balistoides conspicillum*	R	1
Ostraciidae	*Ostracion cubicus*	O	6
Diodontidae	*Diodon holocanthus*	C	9

structure of the fish assemblages at this reef site has been described by Shao and Chen (1992). The average Sorensen similarity coefficient values of the species composition as a function of the time interval (in months) were in the range of 0.4–0.7 with an average of 0.55. These values were similar to those calculated for natural reefs near to the ash reef site. Nevertheless, the individual numbers of each species were quite different, e.g. the large schools of commercial species seen on the artificial reefs were not usually observed on the natural reefs.

CONCLUSION

Our results show that all the methods of fly-ash stabilization (using lime, cement, or waste carbide) satisfy the requirements of the Environmental Protection Agency of Taiwan, for ocean deployment.

Through long term underwater observations *in situ* on large full-scale reefs made with a high percentage of PFA, the effectiveness and durability of ash reefs was found to be as good as that of concrete. The coal ash reefs attract fish and are settled by benthic organisms. Thus we believe that using coal ash from coal-fired power stations to construct artificial reefs in tropical waters has the same environmental compatibility and fishery enchancement potential as has been demonstrated in temperate waters.

In Taiwan, 1,532,250 metric tons of coal ashes were produced by Taiwan Power Company in 1992. Half of this, 762,886 metric tonnes were used, mostly (91.2%) in concrete production. The surplus waste ash could be used in place of concrete for constructing artificial reefs. However, public opinion shows a resistance to using the ash to construct artificial reefs because of the possible negative environmental impacts and some misleading or incorrect information.

Thus, there is a need for public education and dissemination of the correct data. This aspect of support for the related research projects should became very important in the future. After the conceptual barrier against acceptance of using stabilized ash has been overcome, then fly ash wastes can be utilized positively in large quantities to reduce the cost of building artificial reefs.

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