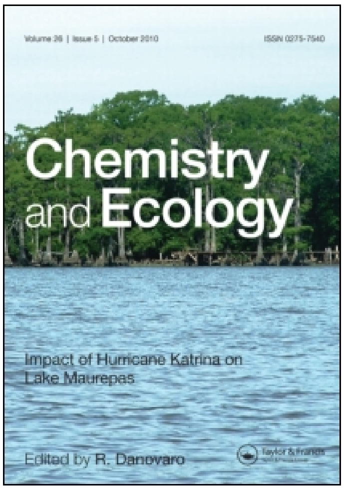

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POSSIBLE USE OF ASH RESIDUES FOR THE CONSTRUCTION OF ARTIFICIAL REEFS AT SEA

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Utilization of ash residues, including coal ash, oil ash, and municipal solid waste combustion ash, for the construction of artificial reefs at sea has been investigated by many researchers throughout the world for nearly 20 years. Both laboratory and field studies have shown that an artificial reef made of stabillized ash-concrete (SAC) has had no adverse effect on the marine environment. Indeed, published studies have shown that fish counts increase around SAC reefs owing to an abundance of colonizing organisms and to protection provided by cavities within the reef structures. However, public and regulatory resistance to the use of SAC for artificial reef construction at sea is still very strong in certain countries due to concern for possible negative environmental impacts, primarily in the area of bioaccumulation of elements or compounds originating from the ash component of SAC.

In this paper, technological feasibility of using ash residues for artificial reef construction is presented, based on the available 20 years of scientific data, including engineering workability, physical integrity, chemical leaching potential and biological effects. More important, we also identify conceptual barriers for the acceptance of using SAC for the construction of ocean reefs and suggest approaches to overcome these barriers.

KEY WORDS: coal, oil, incinerator ash, artificial reef, public perception, regulatory resistance.

INTRODUCTION

History of Ash Reef Research

In early 1970s a group of scientists at State University of New York (SUNY) at Stony Brook started the first systematic research on the use of coal fly ash to prepare stabilized ash concrete (SAC) for the construction of artificial reefs at sea (Seligman and Duedall, 1979; Roethel, 1981). The Coal-Waste Artificial Reef Program (C-WARP) was initiated in 1975 involving comprehensive laboratory studies (C-WARP, 1979; Parker *et al.*, 1982) and, in 1979, an experimental reef composed of 15,000 SAC blocks (18 cm × 18 cm × 40 cm for each block) was placed off the south coast of Fire Island, New York (Duedall *et al.*, 1985). The aims of the 5-year monitoring programme were to investigate the rate and extent of colonization by fouling organisms, the attraction of fish by the reef, the chemical and engineering behaviour of SAC reef units in the ocean, and the overall environmental acceptability of a relatively large number of SAC blocks placed into the ocean.

The work of C-WARP was recognized internationally. Soon after C-WARP was initiated in the United States, Japan began to use the technology to build and test huge coal ash structures (Suzuki, 1985; 1991). In Japan, SAC was used to make large "fish houses" and to fabricate large-scale upwelling structures to increase the turbulent transport of nutrients from near the bottom upward into the photic zone. Japanese technology focused almost entirely on engineering designs to enhance fishing harvest and to increase overall productivity.

In 1983, a group of scientists from Taiwan visited the C-WARP team at SUNY, Stony Brook. Soon after they returned to their country, the Taiwan scientists created an ash reef research programme (Chen, 1987). In 1984, an artificial reef consisting of 2,300 SAC blocks (40cm × 30cm × 28cm for each block) was emplaced in southwestern Taiwan waters. The Taiwan programme initiated a 3-year monitoring study to investigate epifaunal colonization on the reef blocks, to determine the effectiveness of the reef for attracting fishes, and to evaluate the durability of utilizing coal ash reefs in the ocean. As a result of the research programme, an ash reef application was adopted as one of the alternatives to manage coal waste produced by the Taiwan Power & Light Company (Kuo and Pon, 1989).

In 1984, an oil ash reef programme was created in Florida, USA, at Florida Institute of Technology. In 1987 an experimental ash reef was emplaced in the Atlantic Ocean off central Florida's east coast (Kalajian *et al.*, 1989). A 2-year monitoring study was conducted to determine the engineering performance, chemical stability, and biological function of this SAC reef unit in the ocean (Duedall *et al.*, 1992).

In 1989, another comprehensive coal ash reef programme was initiated in the United Kingdom (Collins *et al.*, 1990); some aspects of this programme continue (Collins and Jensen, 1994). The project was funded initially by the UK power industry who sought an alternative to the current practice of dumping raw ash at one site in the North Sea. A primary aim is to investigate the environmental compatibility of the SAC used as reef material by heavy metal analysis of SAC blocks retrieved from the sea to determine whether any leaching or chemical changes are occurring. Biological colonization and potential bioaccumulation of metals are being investigated.

In 1990, a SAC reef research programme was created in Italy (Relini *et al.*, 1994). The aims of the ongoing Italian study are to obtain scientific data during a monitoring programme on the behaviour of SAC and on the interaction between the SAC blocks and marine organisms, in particular the macrobenthos. Table I summarizes the worldwide research groups conducting ash reef studies and their current status.

Status of Ash Reef Research

From a review of the history of ash reef research, involving more than twenty years of ash reef research, one might assume, in the absence of demonstrated adverse effects, that the use of ash for reef construction would have world-wide acceptance. However, this seems to be true only for Japan and Taiwan, where the construction of ash reefs at sea has been considered seriously as an alternative ash waste management strategy. In the United States, the first country to undertake research on ash reefs, the construction of ash reefs is still in the research stage rather than even the pilot stage. At present no large scale ash reef construction has been promulgated. Parallel research in UK (Collins and Jensen, 1994) and Italy (Relini *et al.*, 1994) has confirmed the lack of

Table I World-wide ash reef research groups and their status.

Reef Type/Country	*Current Status*
Coal Ash Reef	
USA	some research activities
Japan	large scale practice
Taiwan	large scale practice
England	research in progress
Italy	research in progress
Oil Ash Reef	
USA	research completed; no follow-up large scale operation
Waste-to-Energy Ash Reef	
USA	some research activities

adverse environmental effects, yet regulatory and public acceptance of the use of SAC blocks for reef construction is still a barrier.

CASE STUDY

For the purpose of this paper, which is to document the reasons why the use of SAC for ocean reef is meeting resistance, two research projects are presented: the Stabilized Oil Ash Reef Program (SOARP and the Waste-to-Energy Ash Concrete Ocean Reef Program (WACORP). Both were conducted by the ash research group at Florida Institute of Technology (Florida Tech), Melbourne, Florida, USA (Shieh, 1994). We now discuss briefly the scientific approaches, the specific findings, and the outcome of the studies carried out in both SOARP and WACORP.

Scientific Approaches

The ash research group at Florida Tech involved engineers, chemists, and biologists working as a team. The group used scientific methods to evaluate SAC for reef construction. Both laboratory investigations and field monitoring studies were conducted to test hypotheses of the reef application and to evaluate the properties of SAC in sea water. The experiments conducted in the laboratory were designed to ensure that needed information was collected before a field study could be carried out. Based on the results of laboratory studies and the characteristics of the selected reef site, a set of hypotheses and a comprehensive monitoring programme were then developed. With a permit to be issued by Florida's regulatory agency, the experimental ash reef would then be emplaced at a selected site. After reef construction the field study was carried out immediately, according to the previously approved monitoring programme. In 1987, a two year monitoring study was initiated in the SOARP. However, no field study was conducted in WACORP which will be discussed under "barriers to acceptance of ash reef".

A. Laboratory Studies

Studies conducted in the laboratory involved engineering, chemical and biological investigations. Table II shows properties investigated in the ash reef research programme. In general, engineering studies involved determination of physical properties of ash, selection and testing of a number of mix designs, and evaluation of engineering characteristics of the ash reef unit to ensure that a SAC reef block could perform successfully in the sea. Chemical studies involved element determination, mineral identification, and chemical leaching studies to determine composition of the SOARP material and its leaching characteristics. Biological studies involved bioassays and toxicological studies to determine the effect of the SAC on marine organisms. For each component investigated, control reefs made of conventional concrete blocks were used for comparison of properties and performance.

B. Field Monitoring Studies

Following the completion of laboratory studies, a monitoring programme (Table III) was then developed based on the laboratory findings and the oceanographic characteristics of the selected reef site. The programme was designed to collect field information to meet the primary goals of the monitoring study, which were to ensure that SAC had no adverse effect on the marine environment as well as on marine organisms and to

Table II Laboratory studies conducted in SOARP and WACORP.

Studies	*SOARP*	*WACORP*
Physical characterization		
particle size distribution	x	x
moisture content	x	x
absorption of water		x
bulk density	x	x
Engineering investigation		
workability	x	x
unit weight	x	x
resistance-to-impact	x	x
compressive strength	x	x
split tension strength		x
modulus of rupture		x
shear strength		x
Chemical investigation		
elemental determination	x	x
chemical leaching	x	x
mineralogy	x	x
organic analysis	x	x
dioxins and furans		x
Biological investigation		
phytoplankton bioassay		x
toxicological evaluation	x	x

Table III Monitoring studies designated for SOARP and WACORP.

	SOARP	*WACORP*
Engineering monitoring studies		
unconfined compressive strength	x	x
split tensile strength	x	
fault/crack monitoring	x	x
surface hardness	x	x
storm damage	x	x
critical engineering criteria	x	x
Chemical monitoring studies		
leaching rates	x	x
uptake rate of Ca and Mg	x	x
mineral formation		x
Biological monitoring studies		
fish communities	x	x
fouling communities	x	x
benthic infauna	x	x
Bioaccumulation monitoring studies		
Arsenic		x
Cadmium	x	x
Chromium		x
Copper	x	x
Iron	x	x
Lead	x	x
Mercury		x
Nickel	x	x
Vanadium	x	
Zinc	x	x
Organic components	x	x

determine the engineering performance of the reef. In field monitoring studies a control exposure of conventional concrete blocks was always studied in parallel with observations on experimental SAC units.

The elements of any ash monitoring programme would vary because of the different types of ash used and the specific environmental conditions at the reef site. In general, the four major elements of investigation included aspects of engineering, chemistry, biology (at the community level) and the bioaccumulation of leached reef components. In SOARP engineering monitoring followed changes in compressive strength of individual SAC reef blocks over time, any cracking of SAC units, movement by currents and coverage or burial by sediments or moving sand. Chemical monitoring determined leaching rates of elements of concern and measured changes in elemental concentrations of SAC and the ambient sea water. Biological monitoring followed the colonization by organisms on and around the reef, identifying species and abundance. Bioaccumulation monitoring determined possible accumulation of contaminants, such as trace metals or polyaromatic hydrocarbons (PAHs), in organisms on or around the reef.

Specific Findings

By modifying the original mix designs developed by the C-WARP group at SUNY, Stony Brook, researchers at Florida Tech successfully demonstrated that oil ash and municipal waste combustion (MWC) ash could be turned into a solid, non-friable concrete product (Kalajian *et al.*, 1989; Shieh *et al.*, 1990). Laboratory studies showed that both oil ash concrete and MWC ash concrete retained their physical integrities in sea water for very long periods of time, and their chemical leaching was minimized by stabilization (Breslin, 1986; Kalajian *et al.*, 1989; Shieh and Duedall, 1994; HDR Engineering, 1991).

The findings of field studies undertaken by SOARP (Duedall *et al.*, 1992) were that the oil ash reef was colonized rapidly by fouling organisms, that fish were attracted to the reef site within one month after reef construction, and that there were no significant differences in abundance or number of species of reef organisms between the ash and the control reefs. The physical strength of the oil ash reef unit was maintained and no cracking was found, although some surface softening was observed. Elements were retained overall in the reef blocks, although some calcium and vanadium were lost from the outer surface of the block (to < 1 cm thickness). No accumulation of metals was found in fish, while in some fouling organisms, only nickel and vanadium were found at levels three to four times greater than in organisms living on the control blocks.

Outcome of the Study

To date, the 8 and 2 years' study involved in the SOARP and WACORP programmes, respectively, have produced 2 technical reports, 15 Masters theses and 5 PhD dissertations, as well as 13 published scientific papers (Breslin and Duedall, 1987, 1988; Shieh and Duedall, 1988; Nelson *et al.*, 1988; Metz and Trefry, 1988; Kalajian *et al.*, 1989, 1990, 1992; Shieh and Wei, 1990; 1991; Frease and Windsor, 1991; Hamilton *et al.*, 1993). These have testified to the benign consequences of the experimental ash reef construction. Yet the final outcome of these US programmes was that no pilot projects were sanctioned even after these comprehensive studies. This unexpected outcome requires some analysis why conceptual barriers still prevent acceptance of SAC reefs at sea.

BARRIERS TO THE ACCEPTANCE OF ASH REEFS AT SEA

What are the "blocking factors" preventing the use of SAC for reef construction at sea? We might distinguish between technological and the conceptual (emotional, subjective, psychological) barriers.

TECHNOLOGICAL BARRIERS

Some basic scientific information limits the complete acceptance of the use of SAC reefs, for instance the accumulation of nickel and vanadium in fouling organisms might be considered an adverse effect. Is this potentially harmful to the organisms, or to other organisms in the food chain or to human health? Is it within the range of natural variation? Many of the early fouling organisms are tunicates, known to accumulate vanadium in uncontaminated environments—Stoecker (1980) showed that this could be more than 3 orders of magnitude greater than the ambient medium. Baseline studies are needed to demonstrate that metals of anthropogenic origin are accumulated to a faster or greater extent than those naturally occurring. A further objection might be that more time (say more than a decade) is required to establish the long term consequences of the reefs.

CONCEPTUAL/SUBJECTIVE BARRIERS

Public perception, evidently subjective rather than objective, is more critical, or the only reason why the use of SAC for reef construction is not accepted. Bewers (1994, this issue) discusses the declining influence of scientific objectivity on marine environmental policy.

In Japan and Taiwan, there is strong reliance on sea food for protein in human diet. Both countries have high population levels, and their land areas are small. Wise and broad use of ocean resources, now and in the future, is critical. In contrast, in the USA, a country with a large area and a relatively small population density, most people consider the ocean to be untouchable. If there is still an abundant land space, providing a surplus of agricultural produce and room for solid waste disposal, why disturb or use the ocean resource? This appears to be the reason why many, especially those living in the coastal area, vote NIMO ("not in my ocean") to the construction of SAC reefs, disregarding the positive scientific validity of findings from SOARP and WACORP, or those from studies overseas. While the longer-term fate (> decade) of artificial reefs may still be in question, this objection seems not to have been raised as a serious issue. The county agency supporting the WACORP study filed a permit application for a field demonstration project with the next higher level of government, the State of Florida, but the county withdrew its application prior to decision by the regulatory agency, apparently on the basis that the site had been designated as an "Outstanding Florida Water (OFW)", which allows no change or development of the site. It was recommended that the county applicant select an alternative site outside the "boundaries" of the designated OFW, disregarding the fluid nature of sea water and the inappropriate concept of a "barrier" to its circulation.

A further objection is the concept of "zero discharge", requiring that anything placed in a water body should not release material to the surrounding water; the "average" concentration of elements in sea water was used as the deciding criterion. However, natural processes in the ocean do not follow this principle (e.g. river discharges, or underwater vents), nor do other fixed or mobile structures (e.g. jetties or ships). Any or all of these activities may release metal-enriched fluids with concentrations of ten to a thousand times greater than "average sea water" concentrations. A distinction in level of contamination from anthropogenic impact and natural processes can seldom be made.

WHAT SOLUTIONS ARE AVAILABLE?

Research needs

The following suggestions are made to resolve the technological barriers:
1. Engineering: Studies have demonstrated that ash blocks are stable in the marine environment. Research should focus on the design of reef units so to improve function (Duedall and Champ, 1991; Nakamura *et al.*, 1991), i.e. to attract fish and other useful organisms, as well as to improve productivity.
2. Chemistry: Chemical findings should be tied to the engineering and biological studies, both in the laboratory and in the field. The longer-term (decadal) fate and transformations of reef constituents should be monitored.
3. Bioaccumulation: This justifies a greater level of investigation. The critical level (for ocean health or human health) of accumulated materials which does not cause harm to the ocean community or to human health should be specified. Again this might be considered on a more than decadal time-scale. Much needs to be done also to establish reliable baseline data against which enhanced concentrations or effects can be measured.

Education

Public education is acknowledged to be an effective mechanism for developing objective, rather than subjective, thinking. Differences in the public and professional expert judgement on the risks of a variety of activities have often been highlighted. More recent surveys have shown that, through public education, for instance on the risks of smoking and alcohol use, that public and professional views can converge. In the case set out here, much needs to be done to develop public knowledge and understanding, as well as an objective, even healthily sceptical, approach to the proposal. The balance of alternative options for waste disposal have also to be set out, so that an informed choice can be made.

CONCLUSIONS

Acceptance of the use of stabilized ash concrete for artificial reefs at sea can occur only when scientific data are judged sufficient, and when the public can be convinced of the validity of the scientific findings, of the lack of adverse effects, and that this is a preferred option for the disposal of ash wastes produced every day by a variety of human activities. This involves additional effort, both to strengthen research and to encourage interaction between scientists and the public.

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