Coral Rehabilitation Using Steel Slag as a Substrate

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***Abstract*- Many researches studied the corals rehabilitation using different techniques all over the world and recorded accepted results. The present experiment presents a new technique and methodology (according to the International Patent) for coral reef transplantation and rehabilitation using Electric Arc Furnace-slag as a substrate for the transplanted corals. Slag is composed mainly of iron oxides (38.07-54.73%), calcium oxides (24.49-34.58%) and silicon oxides (10.23-14.71%) as major constituents, which are chemically stable under the oceanographic conditions throughout the experiment time. In addition, a thin calcium carbonate layer was precipitated on the slag surface from the water column. Three sites were selected to evaluate the steel slag efficiency for coral transplantation. 550 branches and fragments of live corals- *Acropora, Stylophora, Favia, Favites, Goniastera* and *Turbinaria* were fixed on the slag by epoxy materials to transplant. After 22 months, about 70.18% of the transplanted corals survived. That the percentage was suddenly dropped and decreased to 49.27% after 24 months may be due to the effect of flood, high turbidity, and the raised water temperature. Finally, the study recommended by using steel slag as a suitable substrate for coral transplantation and larval settlements of the different coral types.**

Keywords*- *Coral Reefs; Restoration Technique; EAF Slag; Red Sea

I. INTRODUCTION

Slag is resulted during the waste removal mechanism in metal smelting and control re-oxidation of the final liquid product before casting. It is a partially vitreous by-product of smelting ore separating the metal fraction from the worthless fraction. Slag composed mainly of metal oxides mixture, in addition to metal sulphides, carbonates, and metal atoms in the elemental form. Steel slag is used in cement production, reducing CO_2 emissions by around 50% [1], as coastal marine blocks to facilitate coral growth thereby improving the ocean environment and in restoring shoreline environment [2] from erosion, substrate for mangrove rehabilitation [3], as its use in the artificial reefs for seaweed and rehabilitation of bleached corals.

Nandakumer et al. [4] found that a great number of algal species were growing over the slag much more than the concrete blocks substrate during the algal transplantation experiment on steel-making slag and concrete in the seawater off Chiba, Japan. They attributed that to low pH value of slag blocks relative to concretes. Oyamada et al. [5] developed a restoration method for coral reef implanting in Tokyo using marine block (slag) as a substrate and as a pole to stimulate the coral larvae settlements. They proved that, marine slag blocks don't hinder the growth of coral and can be functioned as an artificial substrate for coral transplantation. Many other researchers thereby used the treated slag for different purposes such as: marine plants transplantation [6], coral recruitments settlement in a developmental process of the coastal environment assessment system [7], fish farming and coral recruitment [8] and the growth of juvenile Acropora and mass spawning in Sekisei lagoon, Okinawa [9, 10].

The purpose of this study is to examine a modified method in the transplantation of coral reef fragments using steel slag by-product as a substrate in artificial lagoons and the natural coral localities in sea in order to apply this method in a wide scale for coral reef rehabilitation in the damaged areas of the Red Sea.

II. MATERIALS AND METHODS

A. The Study Area

The present experiment was applied in three different sites; site 1 was selected in front of the National Institute of Oceanography and Fisheries (NIOF), 5km north of Hurghada at the coordinates, 33° 46' 27" E and 27° 17' 05" N at a depth of 2-3m. Site 2 was selected at El-Gouna at 1m depth (33° 40' 56" E and 27° 22' 39" N), 22km north of Hurghada ; while site 3 was an artificial lagoon (33° 40' 51" E and 27° 22' 45" N) at El-Gouna, 22km north of Hurghada, as shown in Fig. 1.

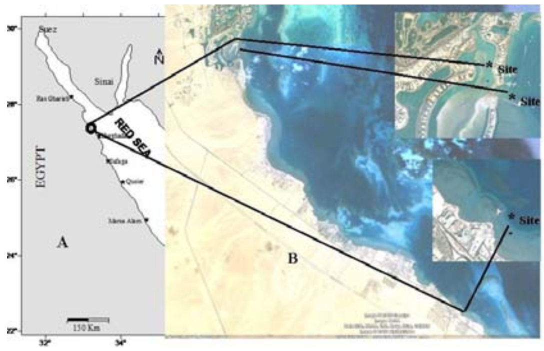

Figure 1 The location map of the studied sites

B. Methods

540 pieces of steel-slag (Electric Arc Furnace-Slag or EAF-Slag) brought from Ezz (Iron-steel factories, Egypt) were used as substrates for the transplantation of coral specimens, these slag pieces are of different sizes and irregular shape patches with a diameter varied between 25cm and 35cm and a height of about 15cm. Detailed analysis for the used slag was carried out several times before the experiment and during the experiment (after one year and two years of transplantation) to determine the chemical effect of the seawater on the slag constituents. The used slag is Electric Arc Furnace-Slag (EAF) and was brought from Ezz Iron-steel factories; moreover, the authors present an international patent for this method and get it at 1 April 2010 (see appendix).

The experiment duration was 24 months (May/2008 to April/2010). Coral specimens were collected from damaged and broken reefs using SQUBA diving and then transported inside plastic bags to the transplantation sites. At site 1, the collected coral specimens were fixed over ten slag stones with epoxy material mixed with hardener for quick hardening and fast fixation. At the other two sites, the collected coral specimens were fixed over 320 slag stones at site 2 and 210 stones at site 3 using a mixture of epoxy and seawater cement. There are 20 transplanted coral samples at site 1, 320 samples were transplanted at site 2, and 210 samples were transplanted at site 3 representing branching, massive and encrusting coral forms. The most frequent and dominant genera were Acropora and Stylophora in addition to Favia - Favites – Goniasterea - Montipora – Echinopora and Turbinaria.

The experiment was started by estimating the solidified rate of the used epoxies. Solidification process takes 30 minutes for the epoxy mixed with hardener and did not exceed 20 minutes for the mixture of epoxy and seawater cement. The coral parts were fixed over the slag stones using the obtained fixative materials then immersed in seawater. The mortality rate and survivorship rate of the transplanted corals as well as environmental conditions (sedimentation rate, temperature, and pH) were recorded during the experiment. The chemical composition of the used slag (surface and in-core) was analyzed using Pnalytical Axios Advanced (XRF) and Brucker Axs-DS Advance instruments before, after10 months and at the end of the experiment (24 months) at the Central Metallurgical R & D Institute to determine any chemical changes in the slag composition.

III. RESULTS

A. Slag Metal Analysis

The chemical composition of the slag by-product before and during the experiment was summarized in Table Ⅰ During the experiment, the chemical analyses of the used slag illustrated more than 18 metal oxides in addition to a thin layer of the calcium carbonate coated the outer surface of slag in addition to some elements traces. The most common oxides were Fe-Oxides, CaO and SiO2 representing the range of 38.067%-54.727% for Fe-Oxides, 24.486%-34.58% for CaO and 10.23%-14.707% for SiO2.

TABLE I THE PERCENTAGE OF CHEMICAL ANALYSIS AND ELEMENTAL COMPOSITION OF THE STEEL SLAG

Elements	B. (surface)	D. (surface)	A. (surface)	A. (in-core)
Na_2O	0.054	0.066	0.252	0.12
MgO	3.624	2.595	3.476	2.916
Al_2O_3	5.052	4.728	3.93	3.371
SiO_2	14.707	14.41	11.101	10.23
P_2O_5	0.541	0.499	0.407	0.396
SO_3	0.165	0.284	0.281	0.194
K_2O	0.013	0.017	0.037	0.011
CaO	34.58	33.092	24.524	24.486
TiO_2	0.287	0.473	0.37	0.378
V_2O_5	0.111	0.112	0.074	0.069
Cr_2O_3	0.547	0.756	0.652	0.648
MnO	2.085	2.97	2.086	2.198
Total Fe-Oxides (FeO & Fe_2O_3)	38.067	39.34	52.016	54.727
SrO	0.003	0.003	0.033	0.034
ZrO_2	0.011	0.015	0.014	0.015
MoO_3	0	0.206	0	0.032
BaO	0.002	0.07	0.068	0.084
WO_3	0	0.041	0	0
Cl	0	0	0.281	0.091
ZnO	0	0	0.017	0
Others (including $CaCO_3$)	0.151	0.323	0.381	0

A) After the experiment; B) Before the experiment; D) During the experiment

B. Settlement of Marine Organisms

After 3 months of the experiment, a thin layer of CaCO3 (1 to 2 mm) was coated the slag surface in Fig. 2. This layer provides a suitable substrate for many marine larval settlements such as Tridacna sp. and many types of algal flora as in Fig. 2, in addition to the settled Modiolus sp., subsequently, the slag had became a part of the marine constituents with time, where it is difficult to differentiate between them and the natural substrate in the environment before and after transplantation, see Fig. 3. In addition, many fishes were attracted to the stone and the transplanted corals, which feed on the algae settling on the stone. Also, the survived transplanted corals reproduced asexually, grow, and increased in size, as illustrated in Fig. 4.

Figure 2 Formation of thin $CaCO_3$ on the slag surface (left) and *Tridacna* settlement on it

Figure 3 The slag shape before emerged (left) and after emerged in water illustrating the difficulty to distinguish between it and natural stone

Figure 4 Small coral colony at the beginning of study (left) and asexual reproduction with increase in size at the end of study (right) of the same coral

C. Coral transplantation

Thirteen coral species were transplanted in the different sites. 20 coral specimens were transplanted at site 1 belonging two coral forms (branching and massive). After 12 months, only 11 coral specimens were still survived representing about 55% of the total specimens in Tables Ⅱ and Ⅲ; another two specimens were recovered again and restored their life and activities. The rest 35% of coral specimens were died due to the effect of high sedimentation rates, high turbidity, and macro-algal blooming especially during winter shown in Fig. 5. Moreover, the survived species grow healthy and forming a discoid coral plat on the used slag then forming a small growing colony, as in Fig. 6.

TABLE II TOTAL PERCENTAGES OF SURVIVED AND DEAD CORAL SPECIES AFTER 24 MONTHS

Species	Individual No.	Survived (%)	Dead (%)
Acropora humilis	33	3.45	2.55
A. Cytharea	47	4.91	3.64
A. Caltherata	58	5.64	4.91
Echinopora gemacea	7	0.36	0.91
Favia favus	4	0.55	0.18
Favia sp.	4	0.36	0.36
Favites persi	7	0.91	0.36
Favia sp.	1	0.18	0.00
Goniastrea pictinata	3	0.55	0.00
Montipora venosa	12	1.64	0.55
Platygyra daedalea	5	0.55	0.36
Stylophora pistillata	364	29.82	36.36
Turbinaria mesentrina	5	0.91	0.00
Total	550	49.27	50.73

TABLE III THE SURVIVORSHIP AND DEATH PERCENTAGE OF THE TRANSPLANTED CORALS AT THE DIFFERENT SITES

Sites	Total No.	Survived (%)	Dead (%)
Site 1	20	55	45
Site 2	320	53.13	46.87
Site 3	210	42.86	57.14

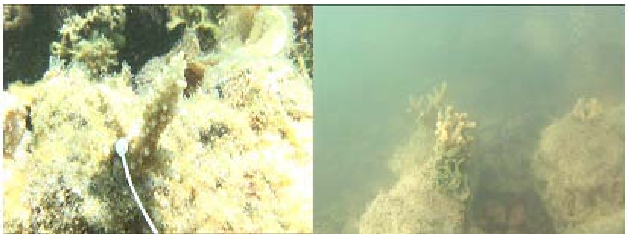

Figure 5 The competition of macro-algae with corals (left) and the effect of turbidity and sedimentation after the flood-water (right)

Figure 6 Survivorship, growth and adaptation of the transplanted corals forming a discoid surface on the used slag

At site 2, a total of 320 coral specimens were transplanted, 235 of them representing 73.44% were survived for about 22 months (May 2008 to Feb. 2010). At site 3 (the artificial lagoon), a total 210 coral specimens were transplanted, 138 of them representing about 65.71% were also survived for the same time. Throughout the period from February to March 2010, the sites (2 and 3) were exposed to intensive flood led to increasing mortality rates of the transplanted corals. At the end of the experiment, 170 coral specimens were survived at site 2 representing 53.13% of the total transplanted specimens and 90 coral specimens were survived at site 3 representing 42.86% as shown in Tables 2 and 3.

D. Some Environmental Factors Affecting Transplantation

Temperature ranged between 18.9 – 29.1 °C, 18.9 – 29.5 °C and 19.6 – 30.5 °C at the studied sites in Table Ⅳ. The pH value recorded during the experiment varied from 7.28 to 7.67 which is suitable for growth of corals and other settling larvae.

TABLE IV WATER TEMPERATURE AND PH AT THE STUDIED SITES

Category	Temperature (°C)				pH
	Autumn	Winter	Spring	Summer	
Site 1	18.9-23.8	18.6-20.3	23.2-26.9	27.8-29.1	7.28-7.39
Site 2	18.9-24.1	18.7-20.6	23.5-27.3	28.1-29.5	7.28-7.62
Site 3	19.6-24.9	18.9-20.8	24.1-27.9	28.9-30.5	7.29-7.67

Sedimentation is the most significant factor affecting the transplantation process at the different sites, where the first site is affected by high sedimentation rate (especially during winter) which resulted from the land filling processes and water currents in the northern part of the Red Sea. Sedimentation rates ranged from 0.0323 to 0.0503 gm/day.cm2 in winter and from 0.0098 to 0.0205 gm/day.cm2 in summer; see Table Ⅴ.

TABLE V THE AVERAGE SEDIMENTATION RATES AT THE STUDIED SITE

Winter	Summer	References
0.0323	0.0205	The present study
0.0437	0.0104	[11]
0.0399 – 0.0503	0.0098	[12]
0.0399	0.0163	Unpublished data

IV. DISCUSSION

The need for restoration practices specifically adapted to the coral reefs ecosystem has led to a number of recent initiatives. Initial efforts were focused on the establishing of artificial reefs [10, 13, and 14] to enhance fisheries production [15 - 18]. Other reef restoration methods using whole coral colony or coral fragments for transplantation were executed by [19 - 25]. The use of novel technology approaches in artificial reefs and future applications were reviewed by [26]. The use of slag as artificial substrata for rehabilitation of reef communities has received little attention to date. The current study used the slag as a substrate for transplanted corals as a novel technique and application to help replenish damaged reef areas [27, 28]. Clark and Edwards [29] suggested that transplantation of mature coral colonies may help to restore degraded reefs, but such procedures should use the broken fragments to avoid damage to the reefs.

During the present experiment, it is pointed out that, the slag components showed minimal chemical changes before and after the transplantation process. However, their components are almost the same, in spite of the formation of a thin layer of calcium carbonate on its surface, that may be due to the stone constituent of a large amount of calcium oxide (40-52% according the slag stone and steel making) that reacts with CO2 from the seawater and form the carbonation. On the other hand it is evident that, the transplanted species were adapted with the new substrate. Where, Acropora spp. and Stylophora pistillata are the most adapted and suitable for transplantation on the EAF-slag. These slags may also attract many other organisms such as fishes and some marine invertebrates. Finally, the transplanted corals form a disc-like base enabling them fixed on the slag substrate and start to form new branches and colony. As well as the growth and the formation of a thin layer of fine algae on the used stone surfaces. On the other hand, macro-algae grew well on the used slag and may have fastened the growth of some larvae of bivalves.

Moreover, the used slag doesn't affect the pH of the seawater at the transplanted sites. Where, slag blocks did not exhibit strong alkalinity in seawater, whereas the pH ranged between 7.28 and 7.67, as in Table 2, this pH is suitable for growth of corals and other settled larvae as. This is in agreement with the findings of [5] who reported that there is no change in the pH and found the slag absorbed CO2 forming CaCO3 on the surface during their experiments on larval settlements on slag blocks. Moreover, this slag is considered as a suitable substrate for further larval settlements such as Tridacna as settled during the present study and algae as well [7]. Takahashi and Yabuta [6] studied the shell and algae transplantation and concluded that the thin layer of CaCO3 which covered the slag block surface have the same substances that form the corals and shells.

Knowledge obtained on the reproductive patterns and settling preferences of the Red Sea corals [30, 31] urged us to assess for the first time the potential use of the steel slag as a substrate for transplantation as an artificial reef. However, the survivorship rates of the total transplanted coral species were found to be related to surrounding factors in the environment and the transplantation procedure. Clark and Edwards [32] suggested that some corals may suffer from mortality and reduced growth as a consequence of the transplantation procedure. However, the present study illustrated that, the overall survivorship of transplanted corals were 70.18% of the 550 coral part and fragments after 22 months then decreased to 49.27% after 24 months (after two experimental years). The mortality rate in the present study is due to flood-water events and turbidity, however the inflicted injuries were more severe than that can be expected to occur during collection of the broken fragments and transport in the same sites.

By comparing the survivorship of the transplanted corals to other and previous studies, it is evident that, the present survived ratio (decreased from 70.18% to 49.27%) is relatively accepted compared to other transplantation studies due to the effect of the flood-water that caused the increase in mortality. On the other hand, the survivorship reached about 51% by [32], 40% in the Philippines [33], 70% at Sumilon Island, Cebu [34] at depths of 1.5-10 m. However, they illustrated that the mortality or coral losses is due to the wave action. The season of transplantation may be an additional factor affects the coral survivorship. Okubo et al [35] pointed out that, all the fragments transplanted in February survived, whereas the July-ones showed low survival rates. This was attributable to the high temperature just after the July transplantation in the summer when the water temperature exceeded 30°C and bleaching was observed in many corals of the transplanted fragments [36, 37]. In the present study, most of the dead coral fragments were transplanted during June/July months and agreed with [36] and [37], that the general survivorship is almost 70.18% after 22 months during the following season where temperature was suitable mostly may be due to warmness caused by slag, this ratio decreased to 49.27% after the flood-water (after two years). Moreover, most of the transplanted corals of the present study were fixed during spring season resulting into a high survivorship.

This agrees with [38]. Finally, sedimentation rate is also an important factor that could affect the survivorship [19], [39] - [41]. The same authors pointed out that, the transplanted species should be selected with care as certain species are significantly more amenable than others to transplantation. Moreover, for some species, the choice of transplanted coral fragments or segments may profoundly influence survival however the considerable loss of transplants is slightly affected by higher energy sites whatever the methods of attachment are [28], [42] - [44]. Moreover, sedimentation and turbidity increased in other sites (sites 2 and 3) due to flood water events causing death and declining most of the transplanted corals.

V. CONCLUSION

During the present study we concluded that:

1 Steel slag was used as a substrate for fixation in the sea bottom environment where it contains some natural elements as calcium oxide (CaO 40-52%), silicon dioxide (15%), iron oxide (30%) and some other elements (MgO, MnO, Al2O3). Hence there is no change approximately in their constituents.

2 A thin layer of calcium carbonate was formed by the reaction between CaO in the slag and CO2 in the sea water, where this carbonate is the same structural material of coral reefs and shells.

3 The survivorship of the transplanted corals is 70.18% after 22 month and decreased to 49.27% due to an expected natural factor (flood-water and heavy rains).

4 The flood-water is an effective factor for coral survival beside the temperature and sedimentation rate. However, some corals have the ability to regenerate and survive again in the natural conditions, but not survived with the effect of flooding.

5 The suitable corals for transplantation are Acroporiidae (Acropora), Pocilliporiidae (Stylophora) and Faviidae (Favia and Favites).

REFERENCES

[1] Euro slag. Legal status of slags, European Slag Association. Report on slag uses, pp. 2-10, 2006.

[2] Environmental Reports. Environmental report I. Reducing environmental loads in production activities, pp. 23-25, 2004.

[3] S. Day, W.J. Streever, J.J. Watts. An experimental assessment of slag as a substrate for mangrove rehabilitation. Restoration Ecology, vol. 7 (2), pp.139-144, 1999.

[4] k. Nandakumer, H. Matsunaga, M. Takag. Microfouling studies on experimental test blocks of steel-making slag and concrete exposed to seawater off Chiba, Japan. Biofouling, vol. 19 (4), pp. 257-267, 2003.

[5] K. Oyamada, K. Watanabe, M. Okamoto, I. Iwata. Reproduction technology of coral reefs using "Marine Block" JFE Technical Report No. 13, pp.46-52, 2009.

[6] T. Takahashi, K. Yabuta. New Applications for Iron and Steelmaking Slag. NKK Technical Review No.87, pp.38-44, 2002.

[7] K.A. Roeroe, M. Yap, M. Okamoto. Development of a coastal environment assessment system using coral recruitment. Fisheries Science, vol. 75, pp.215–224, 2009.

[8] F. Afero, S. Miao, A.A. Perez. Economic analysis of tiger grouper Epinephelus fuscoguttatus and humpback grouper Cromileptes altivelis commercial cage culture in Indonesia. Aquacult International, vol.18 (5), pp. 725-739, 2010.

[9] M. Okamoto, S. Nojima, Y. Furushima, W.C. Phoel. A basic experiment of coral culture using reproduction in the open sea. Fisheries Science, vol.71, pp. 263-270, 2005.

[10] M. Okamoto, M. Yap, A.K. Roeroe, S. Nojima, K. Oyamada, S. Fujiwara, I. Iwata. In situ growth and mortality of juvenile Acropora over 2 years following mass spawning in Sekisei Lagoon, Okinawa (24°N). Fish Sci., vol. 76, pp. 343–353, 2010.

[11] T.A.A. Mohammed. Study of growth and reproduction of some corals at Hurghada region with reference to the effect of some pollutants in the area. Zool. Dept. Faculty of Science. Suez Canal University, 2003, p. 204.

[12] T.A.A. Mohammed, M.A. Mohamed. Some Ecological Factors Affecting Coral Reef Assemblages Off Hurghada, Red Sea, Egypt. Egyptian Journal of Aquatic Research. Vol. 31 (1), PP. 133-145, 2005.

[13] H. Pickering, D. Whitmarsh, A. Jensen. Artificial reefs as a tool to aid rehabilitation of coastal ecosystems: investigating the potential. Mar. Pollut. Bull., vol. 37, pp. 505–514, 1998.

[14] A.T. White, H.P. Vogt, T. Arin. Philippine coral reefs under threat: the economic losses caused by reef destruction. Mar. Pollut. Bull., vol. 40, pp. 598–605, 2000.

[15] A.L. Ortiz-Prosper, A. Bowden-Kerby, H. Ruiz, O. Tirado, A. Caban, G. Sanchez, J.C. Crespo. Planting small massive corals on small artificial concrete reefs or dead coral heads. Bull. Mar. Sci., vol. 69, pp. 1047–1051, 2001.

[16] R.L. Sherman, D.S. Gilliam, R.E. Spieler. Site-dependent differences in artificial reef function: implications for coral restoration. Bull. Mar. Sci., vol. 69, pp. 1053–1056, 2001**.**

[17] A. Abelson, Y. Shlesinger. Comparison of the development of coral and fish communities on rock-aggregated artificial reefs in Eilat, Red Sea. J. Mar. Sci., vol. 59, pp. 122–126, 2002.

[18] H. Schumacher. Use of artificial reefs with special reference to the rehabilitation of coral reefs. Bonner Zool. Monogr., vol. 50, pp. 81–108, 2002.

[19] M.S.A. Ammar, E.M. Amin, D. Gundacker, W.E.G. Müeller. One rational strategy for restoration of coral reefs: application of molecular biological tools to select sites for rehabilitation by asexual recruits. Mar. Pollut. Bull., vol. 40 (7), pp. 618-627, 2000.

[20] L.J. Raymundo. Mediation of growth by conspecific neighbors and the effects of site in transplanted fragments of the coral Porites attenuata Nemenzo in the central Philippines. Coral reefs, vol. 20, pp. 263–272, 2001.

[21] H.E. Fox, J.S. Pet, R. Dahuri, R.L. Caldwell. Coral reef restoration after blast fishing in Indonesia. Proc 9th Int Coral Reef Symp., vol. 2, pp. 969–976, 2002.

[22] H.E. Fox, J.S. Pet, R. Dahuri, R.L. Caldwell. Recovery in rubble fields: long-term impacts of blast fishing. Mar Pollut Bull., vol. 46, pp. 1024–1031, 2003.

[23] U. Lindahl. Coral reef rehabilitation through transplantation of staghorn corals: effects of artificial stabilization and mechanical damages**.** Coral Reefs, vol. 22, pp. 217–223, 2003.

[24] M.S.A. Ammar, M.A. Mahmoud. A new innovated and cheep model in building Artificial reefs. Egyptian journal of aquatic research, vol. 31 (1), pp. 105-117, 2005.

[25] S. Shafir, J. Van Rijn, B. Rinkevich. Steps in the construction of underwater coral nursery, an essential component in reef restoration acts**.** Marine Biology. Marine Biology, vol. 149, pp. 679–687, 2006.

[26] M.S.A. Ammar. Coral reef restoration and artificial reef management, future and economics. The Open Environmental Engineering Journal, vol. 2, pp. 37-49, 2009.

[27] V.J. Harriot, D.A. Fisk. A comparison of settlement plate types for experiments on the recruitment of scleractinian corals. Mar. Ecol. Prog. Ser., vol. 37, pp. 201-208, 1987.

[28] H.T. Yap, P.M. Alino, E.D. Gomez. Trends in growth and mortality of three coral species (Anthozoa: Scleractinia), including effects of transplantation. Mar. Ecol. Prog. Ser., vol. 83, pp. 91–101, 1992.

[29] S. Clark, A.J. Edwards. The use of artificial reef structures to rehabilitate reef flats degraded by coral mining in the Maldives. Bull. Mar. Sci., vol. 55, pp. 726-746, 1994.

[30] Y. Shlesinger, Y. Loya. Coral community reproductive patterns: Red Sea versus the Great Barrier Reef. Science, vol. 228, pp. 1333-1335, 1985.

[31] Y. Benayahu, D. Weil, M. Kleinman. Radiation of broadcasting and brooding patterns in coral reef alcyonaceans. In: Hoshi M, Yamashita O (eds) Advances in invertebrate reproduction 5. Elsevier, New York, pp 323-328, 1990.

[32] S. Clark, A.J. Edwards. Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldives Islands. Coral Reefs, vol. 14, pp. 201–213, 1995.

[33] A.C. Alcala, E.D. Gomez, L.C. Alcala. Survival and growth of coral transplants in Central Philippines. Kalikasan, Philipp. J. Biol., vol. 11, pp. 136 147, 1982.

[34] B. Auberson. Coral transplantation: an approach to the reestablishment of damaged reefs. Kalikasan, vol. 11, pp. 158–172, 1982.

[35] N. Okubo, H. Taniguchi, T. Motokawa. Successful methods for transplanting fragments of *Acropora formosa* and *Acropora hyacinthus***.** Coral Reefs, vol. 24, pp. 333–342, 2005**.**

[36] H. Taniguchi. Measurements of time-averaged intensity of water motion around Akajima Island (in Japanese). Midoriishi, vol. 12, pp. 18–20, 2001.

[37] H. Taniguchi, K. Iwao, M. Omori. Coral bleaching around Akajima, Okinawa I. A report of the September 1998 survey (in Japanese with English abstract). Galaxea, JCRS, vol. 1, pp. 59–64, 1999.

[38] H.T. Yap, R.M. Alvarez, H.M. Custodio, R.M. Dizon. Physiological and ecological aspects of coral transplantation. J. Exp. Mar. Biol. Ecol., vol. 229, pp. 69–84, 1998.

[39] U. Oren, Y. Benayahu. Transplantation of juvenile corals: a new approach for enhancing colonization of artificial reefs. Marine Biology, vol. 127, pp. 499-505, 1997.

[40] C.S. Rogers. Responses of coral reef and reef organisms to sedimentation. Mar. Ecol. Prog. Ser., vol. 62, pp. 185-202, 1990**.**

[41] M. Wittenberg, W. Hunte. Effects of eutrophication and sedimentation on juvenile corals. I. Abundance, mortality and community structure. Mar. Biol., vol. 112, pp. 131-138, 1992.

[42] V.J. Harriott, D.A. Fisk. Accelerated regeneration of hard corals: a manual for coral reef users and managers. Tech Memo 16, Great Barrier Reef Marine Park Authority, 1988.

[43] V.J. Harriott, D.A. Fisk. Coral transplantation as a reef management option. In: Proceedings of the 6th International Coral Reef Symposium, Australia, vol. 2. pp. 375–379, 1988**.**

[44] G.P. Plucer-Rosario, R.H. Randall. Preservation of rare coral species by transplantation: an examination of their recruitment and growth. Bull. Mar. Sci., vol. 41, pp. 585–593, 1987.