Use of steel slag as a substrate for coral transplantation

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Abstract

Many researchers try to restore and rehabilitate corals using many different techniques allover the world. The present study presents and applies a modern technique (according to the international patent) for coral transplantation and rehabilitation based on using electric arc furnace-slag (EAF-slag) as a substrate for transplanted corals. This slag is mainly composed of iron oxides (38.07-54.73%), calcium oxides (24.49-34.58%) and silicon oxides (10.23-14.71%) as major oxides, which in general, were not changed during the experiment. In addition, a thin calcium carbonate layer was formed on the slag surface as a result of the reaction with dissolved CO_2 in water. Three sites were selected to test the efficiency of slag for coral transplantation. 550 coral branches and fragments were transplanted and fixed on the slag by epoxy materials. A total of 70.18% of the transplanted corals survived after 22 months, then the ratio decreased to 49.27% after 24 months due to the effect of some interacted factors as floods and rise of water temperature at site 3 (artificial lagoon). However, sedimentation rate and turbidity are additional limiting factors on coral survivorship. It was finally concluded that, the steel slag is a suitable substrate for coral transplantation, as well as for larval settlements of different species. The most survived species of transplanted corals were *Acropora, Stylophora, Favia, Favites, Goniastera* and *Turbinaria*.

Keywords: Coral reefs, steel slag, restoration technique, Red Sea

1. Introduction

Slag is a partially vitreous by-product of smelting ore separating the metal fraction from the worthless fraction. It can be considered to be a mixture of metal oxides; however, slag can contain metal sulphides and metal atoms in the elemental form. Moreover, slag is generally used as a waste removal mechanism in metal smelting and control re-oxidation of the final liquid product before casting. Slag (steel making by-product) is used in cement production, reducing CO_2 emissions by around 50% (Euro slag, 2006), where it is used in coastal marine blocks to facilitate coral growth thereby improving the ocean environment, whereas the slag by-product is used in restoring shoreline environment (Environmental Report, 2004) from erosion, as its use in the artificial reefs for seaweed and rehabilitation of bleached corals.

Day *et al.* (1999) used the slag as a substrate for mangrove rehabilitation, where their study pointed out that, mangroves planted on slag are under no greater risk of future failure than mangroves planted in naturally occurring substrate. Nandakumer *et al.* (2003) illustrated greater number of algal species as well as cell density on the slag than on the concrete blocks substrate during their experiment of the algal transplantation on steel-making slag and concrete in the seawater off Chiba, Japan. They found the pH of the slag block was near neutral, while the concrete was highly alkaline. This alkaline medium initially reduced the rate of species colonization on the concrete blocks. Oyamada *et al.* (2009) developed a restoration method for coral reef implanting in Tokyo by preparing the marine block (slag) as a substrate for coral larvae using the slag as a pole stimulates the larvae settlement. They proved that, marine block does not hinder the growth of coral and can function as an artificial base or substrate for coral transplantation.

Researchers also documented the treated slag in different purposes such as marine plants transplantation (Takahashi and Yabuta, 2002), coral recruitment as a developmental process of the coastal environment assessment system (Roeroe *et al.*, 2009), fish farming and coral recruitment (Afero *et al.,* 2009) and the growth of juvenile *Acropora* and mass spawning in Sekisei Lagoon, Okinawa (Okamoto *et al.,* 2010). The purpose of this study is to test a modified method in transplantation of coral reef fragments using steel slag by-product as a substrate in both artificial lagoon and natural water. However, application of that method in a wide scale for rehabilitation of damaged areas as a modern technology will be discussed.

2. Materials and methods

2.1. The study area (Figure 1)

The present experiment was applied to three sites; site 1 was selected in front of the National Institute of Oceanography and Fisheries (NIOF), 5 km north Hurghada located at 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 Hurghada; while site 3 was an artificial lagoon (33° 40' 51" E and 27° 22' 45" N) at El-Gouna.

2.2. Methods

540 pieces of slag (steel making by-product slag) were used as substrates for the transplantation of coral parts and branches, these slags were patches of different sizes and irregular shape with a diameter of 25-35cm and a height of about 15cm. It contains high ratios of different oxides. However, a detailed analysis for the slag was carried out several times (before the experiment, during the experiment, one year of transplantation in water and two years after placing in seawater, to determine if their components were changed or not. The used slags are Electric Arc Furnace-Slag (EAF) which 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).

Duration of the experiment was 24 months (May/2008 to April/2010). The coral samples were fixed at site 1 with epoxy material (mixture of two liquefied epoxy materials with hardener for hardness and to quick the fixation process); moreover, a mixture of the epoxy and seawater cement were used for the fixation process at the other two sites to solidify and fix corals faster. During the experiment, ten slag stones were used at site 1 for the first 12 months, then 320 stones at site 2 and 210 stones at site 3 for 12 months more. However, 20 samples of the corals (18 branching and two massive) were transplanted at site 1, 320 samples were fixed at site 2, and 210 samples were fixed at site 3. Coral fragments were collected from the damaged and broken reefs at the studied sites (first and second sites) using SQUBA diving equipments and coral knife and transported using plastic pages to the fixation sites. They represented the following coral forms; branching, massive and encrusting. The most frequent and dominant genera were *Acropora* and *Stylophora*. Other transplanted coral genera were; *Favia - Favites – Goniasterea - Montipora – Echinopora* and *Turbinaria*.

To start the experiment, suitable amount of the fixative material was placed on the slag stone, and then immersed in seawater; before that, coral parts were prepared in plastic bags to be fixed under the sea water, each transplanted coral part was fixed on the slag substrate. The time needed to solidify the epoxy ranged between 20 minutes and 6 hrs according to the quantity of the used material, while for the mixture of epoxy and seawater cement, the time needed did not exceed 15 minutes. Mortality rate and survivorship of the transplanted corals as well as environmental conditions (sedimentation rate, temperature and pH) were determined throughout the study period. Surface and in-core layers of the slag were analyzed to determine its chemical composition. Surface was analyzed 3 times; before, after10 months and at the end of the experiment (24 months). The analyses were carried out at the Central Metallurgical R & D Institute according to the standard mothods of chemical analysis and by using the Pnalytical Axios Advanced (XRF) and Brucker Axs-DS Advance instruments.

3. Results

3.1. Slag metal analysis

Table (1) illustrates the chemical composition of the slag by-product before and during the experiment indicating that the slag is composed of more than 18 compounds during the experiment (mostly oxides) in addition to some other elements which did not more than 0.151% and 0.323%. This ratio doesn't exceed 0.381% after transplantation of corals, where the analysis illustrated about 19 chemical compounds in their structure beside a thin layer of calcium carbonate that appears on the surface of the used slag after transplantation process. Generally, the most common oxides were; total Fe-Oxides, CaO, SiO_2 which represented a ratio of 38.067%-54.727% for Fe-Oxides; 24.486%-34.58% for CaO and 10.23%-14.707% for SiO_2.

3.2. Settlement of marine organisms

After 3 months of the experiment, a thin layer of $CaCO_3$ (1 to 2 mm) was formed on the slag surface as a result of absorbing CO_2 from seawater and reaction with CaO (Figure 2). This layer is the same substance that comprises coral reefs and seashells. However, the slag had many surface cavities, the sizes of which were larger than the marine settling larvae leading to easier settlement and growth on the slag surface. Moreover, slag blocks did not exhibit strong alkalinity in seawater, whereas the pH ranged between 7.28 and 7.67 (Table 2), this pH is suitable for growth of corals and other settled larvae as *Tridacna* sp. (Figure 2). Moreover, a thin layer of fine algae was formed on the used stone which make a difficulty in differentiation between them and the natural substrate in the environment before and after transplantation (Figure 3). In addition, many fishes were attracted to the stone and the transplanted corals, which feed on the algae settling on the stone.

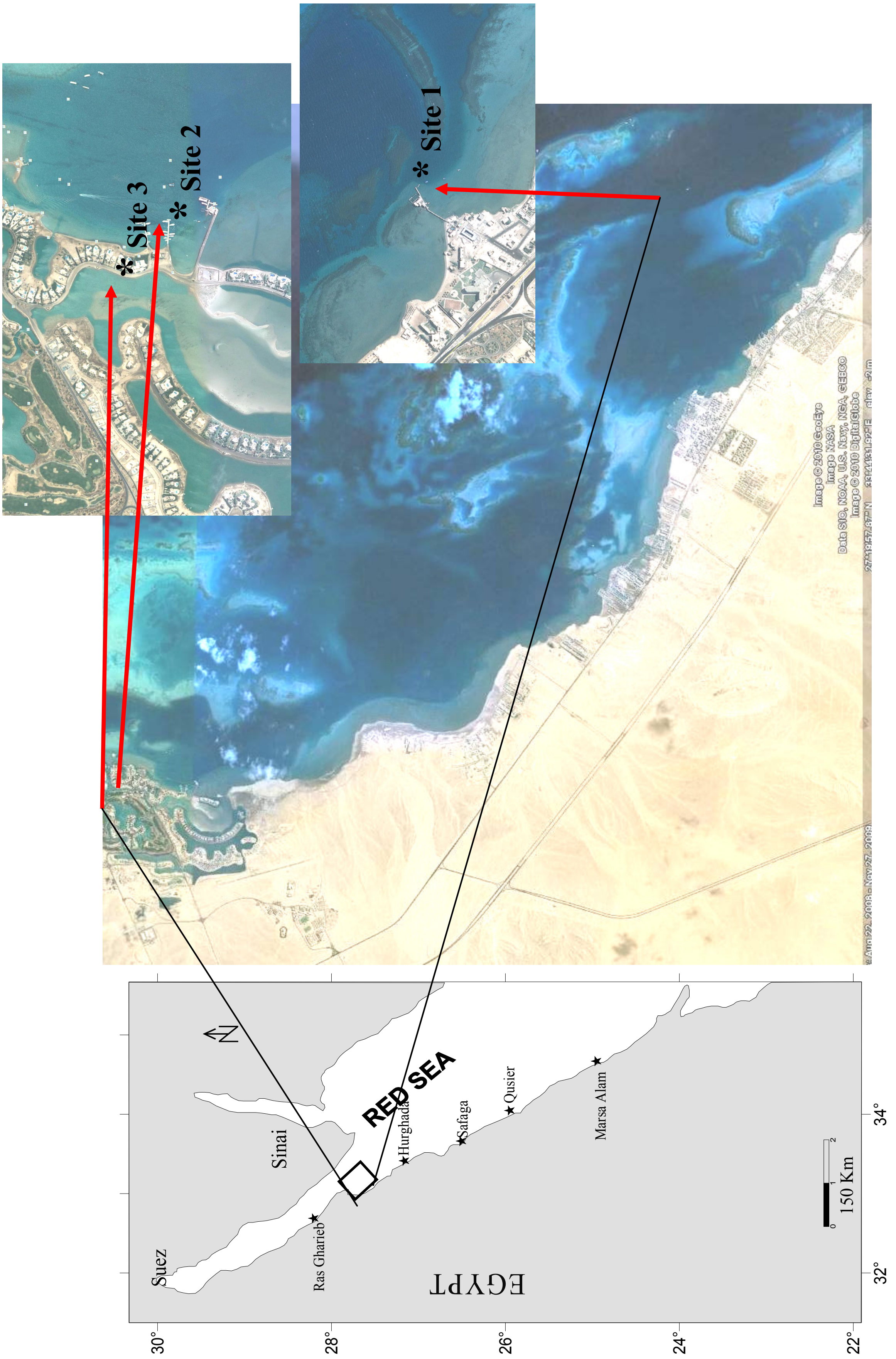

Figure 1. The Red Sea map (A) showing the study sites (B).

Table 1. 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

Table 2. Water temperature and pH at the studied sites.

Category	**Temperature (ºC)**				**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

Also, the survived transplanted corals reproduced asexually, grow and increased in size (Figure 4).

3.3. Coral transplantation

In the present study, 13 coral species (Table 3) were used in the transplantation process at all of the studied sites. 20 coral recruits were used at site 1 representing two coral growth forms (branching and massive). After 12 months, only 11 coral recruits were still alive and have a good condition representing 55% of the transplanted recruits at this site (Table 4). Their polyps were also acclimated to the environment in the protected and semi-protected areas from the sedimentation, water currents and turbidity after transplantation and transferring in the same sites. Moreover, two branches which started to die, regenerated again and restored their life and activities. On the other hand, 35% of coral branches and recruits were seriously affected and died by the effect of sedimentations, water currents, turbidity and macro-algal blooming especially during winter (Figure 5).

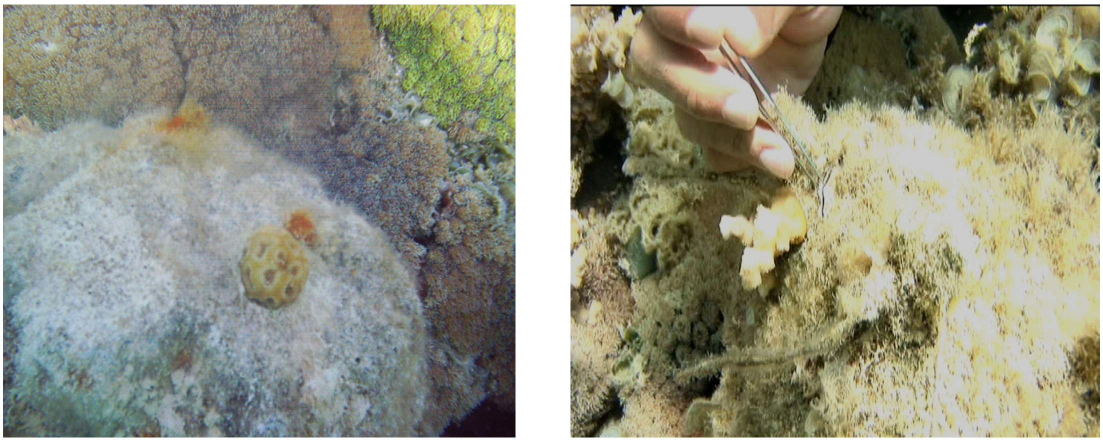

Figure 2. Formation of thin $CaCO_3$ on the slag surface (left) and *Tridacna* settlement on it.

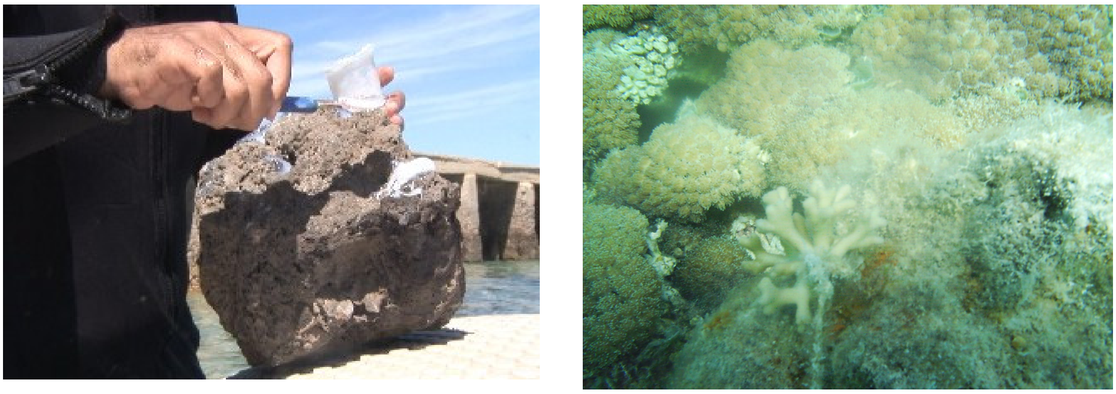

Figure 3. The slag shape before emerged (left) and after emerged in water illustrating the difficulty to distinguish between it and natural stone.

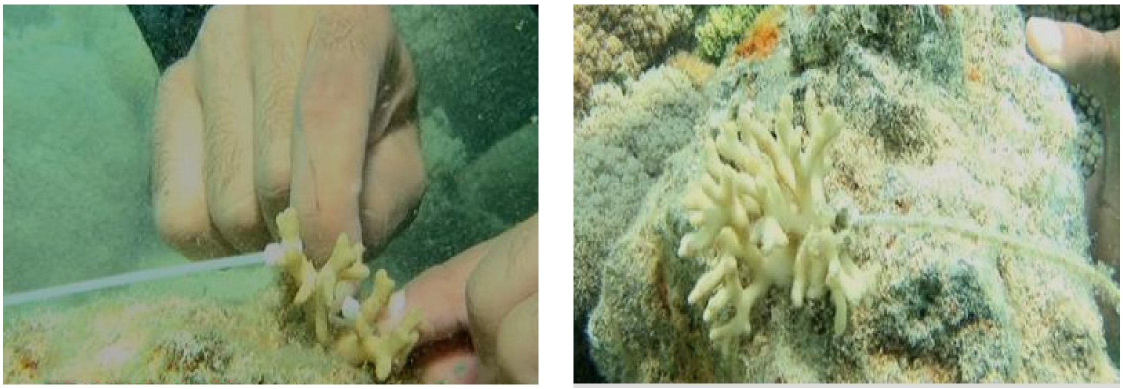

Figure 4. Small coral colony at the beginning of study (left) and asexual reproduction with increase in size at the end of study (right) of the same coral.

A total of 235 coral samples of the 320 transplanted corals representing 73.44% were still alive after a period of 22 months at site 2, but at site 3 (the artificial lagoon), a total of 138 corals of 210 transplanted corals representing about 65.71% were still alive after the same period. During the period February to March 2010, the studied areas (sites 2 & 3) were exposed to heavy rains and water flowage (flood-water), leading to a decreased survival and increased mortality rates. The flood-water caused an increase in sedimentation and turbidity in the studied sites. After 12 months, only 170 coral samples were still alive and survived representing 53.13% of the transplanted samples at site 2 and 90 coral samples representing 42.86% were still alive at site 3 (Table 4). Moreover, most of the transplanted recruits of *Acropora* spp. and *Stylophora pistillata* are adapted and suitable for transplantation on the EAF-slag (Table 3). On the other hand, macro-algae grew well on the used slag and may have fastered the growth of some bivalves (Figure 2). 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 (Figure 6).

3.4. 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. 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 2).

Site 1 is characterized by high sedimentation rate especially during winter, which resulted from the landfilling processes and water currents in the northern part of the Red Sea. Sedimentation rates ranged from 0.0323 to 0.0503 gm/day.cm^2 in winter and from 0.0098 to 0.0205 gm/day.cm^2 in summer (Table 5). Moreover, sedimentation and turbidity increased in other sites (sites 2 & 3) due to flood water events causing death and declining most of the transplanted corals.

Table 3. 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 4. 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

Table 5. The average sedimentation rates at the studied site.

Winter	Summer	References
0.0323	0.0205	The present study
0.0437	0.0104	Mohammed (2003)
0.0399 – 0.0503	0.0098	Mohammed (2005)
0.0399	0.0163	Unpublished data

4. Discussion

The need for restoration practices specifically adapted to the coral reef ecosystem has led to a number of recent initiatives. Initial efforts focused on the establishing of artificial reefs (Pickering *et al.*, 1998; White *et al.*, 2000 and Okamoto *et al.* 2010) to enhance fisheries production (Ortiz-Prosper *et al.*, 2001; Sherman *et al.*, 2001; Abelson and Shlesinger, 2002; Schumacher, 2002). Other reef restoration methods using whole coral colony or coral fragments for transplantation are Ammar *et al.* (2000), Raymundo, (2001), Fox *et al.* (2002 and 2003), Lindahl (2003), Ammar and Mahmoud (2005) and Shafir *et al.* (2006). The use of novel technology approaches in artificial reefs and future applications were reviewed by Ammar (2009). The use of slag as an 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 (Harriot and Fisk, 1987; Yap *et al.*, 1992). Clark and Edwards (1994) 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 other reef areas.

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, causing formation 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 CO_2 from the seawater and form the carbonation. On the other hand it is evident that, the transplanted species are adapted with the new substrate (Tables 3 & 4**).** In addition to the formation of a thin layer of fine algae on the used stone surfaces. However, the used slag not affect the pH of the seawater at the transplanted sites. This is in agreement with the findings of Oyamada *et al.* (2009) who reported that there is no change in the pH and found the slag absorbed CO_2 forming $CaCO_3$ 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 (Roeroe *et al.,* 2009). Moreover, the covered surface of the slag block by $CaCO_3$ is the same substance that comprises corals and shells according to Takahashi and Yabuta (2002) who studied the shell and algae transplantation.

Knowledge obtained on the reproductive patterns and settling preferences of the Red Sea corals (Shlesinger and Loya, 1985; Benayahu *et al.*, 1990) urged us to assess for the first time the potential use of the steel slag as substrate for transplantation as an artificial reef. However, the survivorship rates of the total transplanted coral species were found to be related to

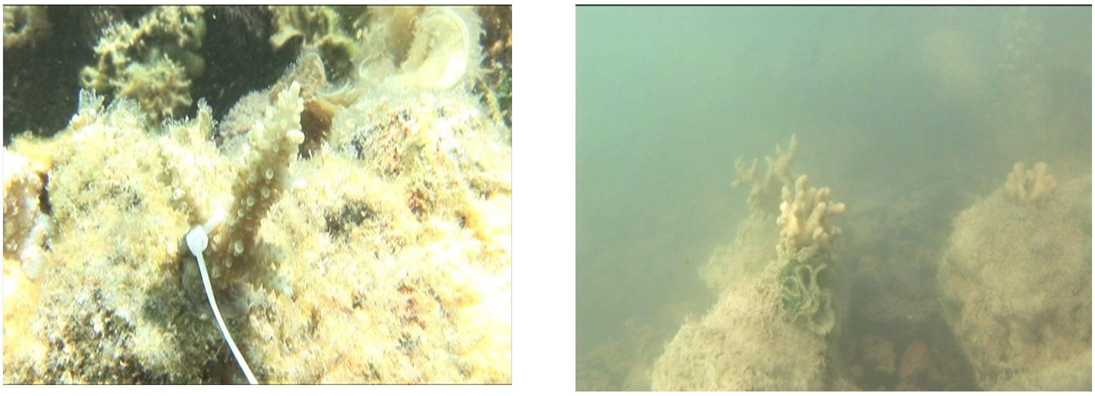

Figure 5. The competition of macro-algae with corals (left) and the effect of turbidity and sedimentation after the flood-water (right).

Figure 6. The competition of macro-algae with corals (left) and the effect of turbidity and sedimentation after the flood-water (right).

surrounding factors in the environment and the transplantation procedure. Clark and Edwards (1995) 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 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 Clark and Edwards (1995), 40% in the Philippines (Alcala *et al.*, 1982), 70% at Sumilon Island, Cebu (Auberson, 1982) 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 affecting coral survivorship. Okubo *et al.* (2005) 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 (Taniguchi, 2001 and Taniguchi *et al.*, 1999). In the present study, most of the dead coral fragments were transplanted during June/July months and agreed with Taniguchi (2001) and Taniguchi *et al.* (1999), then 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 Yap *et al.* (1998). Finally, sedimentation rates are also an important factor that could affect the survivorship (Oren and Benayahu, 1997; Rogers, 1990; Wittenberg and Hunte, 1992; Ammar *et al.*, 2000). 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 (Harriott and Fisk, 1988 a & b; Plucer-Rosario and Randall, 1987; Yap *et al.*, 1992).

5. 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, Al_2O_3). Hence there is no approximately change in their constituents.
2. A thin layer of calcium carbonate was formed by the reaction between CaO in the slag and CO_2 in the sea water, where this carbonate is the same structural material of coral reefs and shells.
3. The survivorship of the transplanted corals are 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*).

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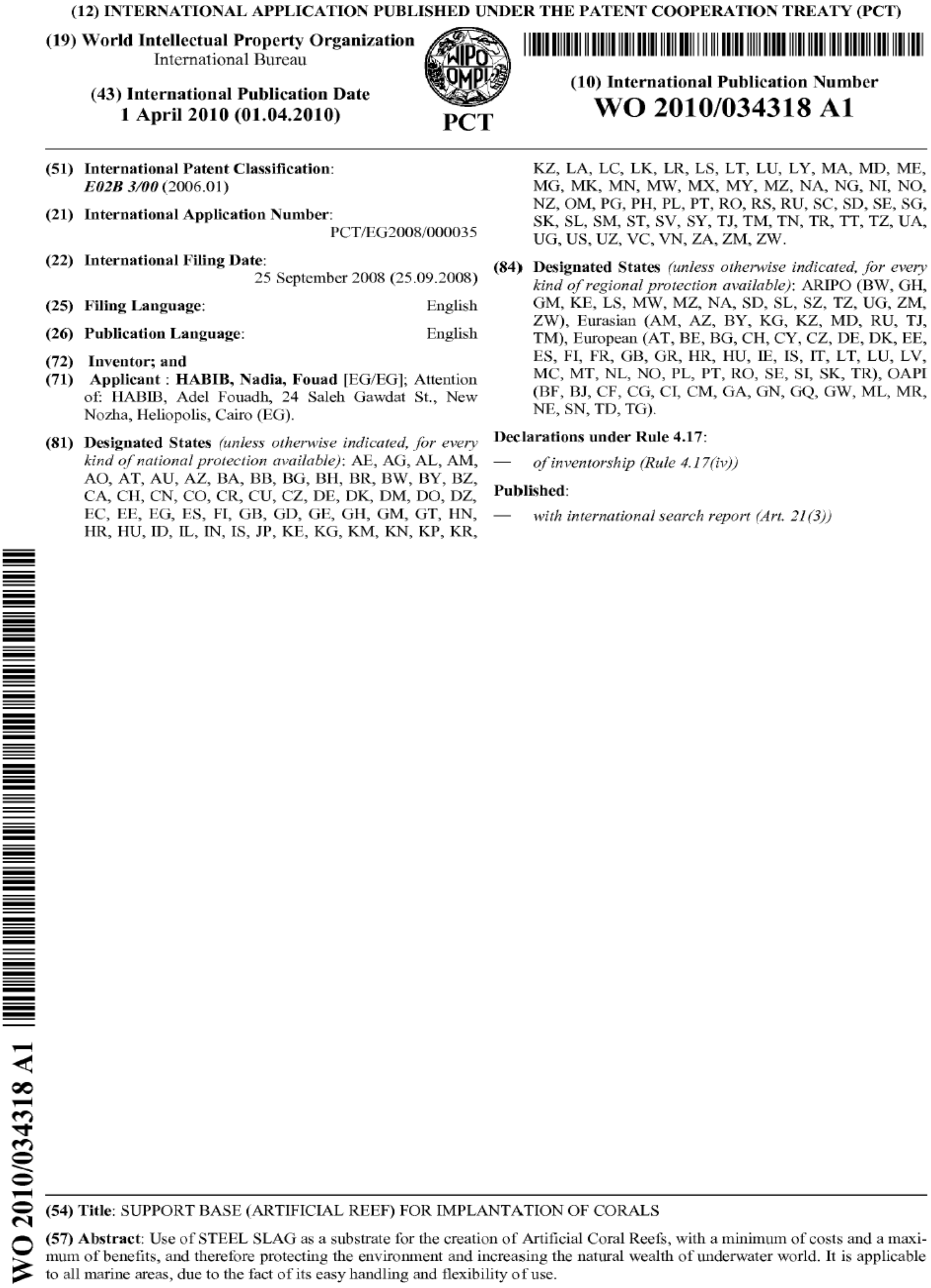
Appendix (International Patent)



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(54) Title: SUPPORT BASE (ARTIFICIAL REEF) FOR IMPLANTATION OF CORALS

(57) Abstract: Use of STEEL SLAG as a substrate for the creation of Artificial Coral Reefs, with a minimum of costs and a maximum of benefits, and therefore protecting the environment and increasing the natural wealth of underwater world. It is applicable to all marine areas, due to the fact of its easy handling and flexibility of use.

استخدام خبث الحديد كقاعدة لاستزراع الشعاب المرجانية

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اعتمدت الدراسة الحالية على استخدام خبث الحديد (المنتج الثانوى لتصنيع الحديد بطريقة القوس الكهربى كما هو بدون معالجة) كقاعدة لاستزراع الشعاب كطريقة تطبيقية حديثة حاصلة على براءة اختراع دولية. ويتكون هذا الخبث أساسا من أكسيد الحديد (بنسب تتراوح بين 38.07-54.73%) وأكسيد الكالسيوم (24.49-34.58%) وأكسيد السيليكون (10.23-14.71%) كقيم عظمى والتى لم تتغير أثناء التجربة. وعلاوة على ذلك تكونت طبقة رقيقة من كربونات الكالسيوم على سطح الخبث نتيجة تفاعل ثانى أكسيد الكربون الذائب فى الماء مع أكسيد الكالسيوم الموجود بنسبة كبيرة فى الخبث، حيث أن هذه الكربونات تحاكى تلك التى يتكون منها الشعاب والأصداف. ومن ناحية أخرى فقد تم استزراع 550 فرع وقطعة من الشعاب ووجد أن حوالى 70.18% منها ظل حيا خلال 22 شهرا من الدراسة وبعد ذلك قلت النسبة إلى 49.27% بعد 24 شهرا كاملا للتجربة فى مناطق الدراسة وذلك بسبب تداخل عدة عوامل أهمها أحداث السيول وارتفاع درجة حرارة المياه داخل البحيرة الصناعية. بالإضافة إلى معدلات الإرساب والتعكير والتى تؤثر على حياة الشعاب المرجانية وتسبب دمارها. وأخيرا فإن أنسب الأنواع التى أمكن استزراعها هى *أكروبورا و أستيلوفورا و فافيا وفافيتس وجونياستريا وتيربيناريا*. ومن ثم فان هذا الخبث يعتبر مناسب لعملية الاستزراع ورسو الطحالب واستقرار وتثبيت الكائنات الأخرى مثل محار *تراىداكنا*.