Marine Life and Coastal Restoration by Utilizing Steel Slag to Create Sea Forest on Sandy Coast of Southwest Taiwan

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***Abstract*—The first Taiwanese in-situ experiment is on trial to develop artificial reefs for marine production in the coastal area of southwestern Taiwan. In this study, we deployed several carbonated BOF slag of reefs in a sandy bed of Fangshan coast. Based on the result of the diving investigation, the benthic sediment consists of sand. The analysis of the 12 times sampling collections indicated that there were 60 families of epibenthic organisms inhabited at Fengkan coast. Nereididae was the maximum quantity of specimen, the minor one was Gammaridea. Nereididae, Portunidae and Trochidae has been captured in almost every investigation. In comparison with artificial reef and non-reef areas has found that many fish near the reef area. On the contrary, there are few fish near non-reef area. There are 23 species of fish had been witnessed at study sites around reefs by visual diver observations. In conclusion, the carbonated BOF slag was suitable for the attachment growth of coral reefs and Fish-gathering. The successful development of marine brick composed of carbonated BOF slag could potentially offer great benefits in promoting artificial reefs function, and play an important role in marine ecosystems.**

Keywords—steelmaking slag, carbonated basic oxygen furnace slag, artificial reef

I. INTRODUCTION

Slag is a broad term covering all non-metallic co products resulting from the separation of a metal from its ore. The chemistry and morphology of slag depended on the metal being produced and the solidification process used. Slags are the main by-products generated during iron and crude steel production. Figure 1 shows a flow chart of slag output for the iron and steel-making processes and the types of slag generated from each process. Once scorned as a useless waste, it is now accepted and specified as it is known to be a valuable material with many different applications [1]. The main types of slags that are generated from the iron and steelmaking industries are classified as follows [2]:

(i) BFS: blast-furnace slag (ironmaking slag)

(ii) SFS: steel-furnace slag

(a) Basic-oxygen-furnace (BOF) slag

(b) Electric-arc-furnace (EAF) slag

(c) Ladle slag (LS)

Generally speaking, iron and steelmaking slags are classified as Blast Furnace (BF) slag or steelmaking slag such as basic oxygen furnace (BOF) or Linz-Donawitz (LD). Steel slag is an industrial by-product obtained from the steelmaking process floats on top of the molten steel. It is a solid output from steel production. In general, Basic Oxygen Furnace slag (BOS) is a main co-products generated during the steelmaking process. With the rapid growth of industrialization, the available land for dispose of large quantities of metallurgical slag like BOS at a landfill site is reducing the disposal cost becomes increasingly higher in all over the world respectively. Steel-making slag, due to its high bulk density and high level of strength, can be used as a construction material for hydraulic engineering purposes.

In Japan, Nippon Slag Association has since 1993 been involved in application technology research for the use of slag as a ground improvement in harbor construction [3] and marine environment improvement technology [4]. As useful recycled materials, iron and steelmaking slags are mainly used in fields and related to a recycling-oriented society [5]. NSSMC and JFE steel corporation in Japan, and POSCO in Korea manufactured artificial reefs for restoration of coastal ecosystem and growth enhancement of seaweed and algae by using carbonated steel slag. A variety of steel slag products such as Beverly® serials, Marine stone® and Triton® has been used in marine ecosystem [6] and [7]. Besides, several new experiments were carried out by JFE group as part of the development of a coral reproduction technology using settlement devices and Marine Block® [8] and [9].

In fact, the steelmaking slag is being generated at a rate of 1.15 million tons per year in Taiwan [10]. It is becoming increasingly important to use steelmaking slag effectively in order to promote resource recycling. In Taiwan, slag has traditionally been used as a component of cement and construction, and as a road ballast. A new technique of

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carbonation treatments for stabilizing steelmaking slag have been applied in Taiwan, and marine application of steelmaking slag are still in progress.

The number of coastal fish species in northern Taiwan has dropped by 75% over the past three decades. Such changes reflect the decline in fish abundance due to overfishing and marine pollution has trashed Taiwan. Artificial reefs have often been used to recover and develop seaweed beds in at least 40 counties [11]. Moreover, seaweed beds play several important roles in biological production, water quality purification, sediment stabilization, and conservation of the detritus food chain and primary consumers. Several studies have been conducted to evaluate the performance of steel slag and CO_2 without supplying cement of marine blocks as artificial reefs on the algal growth. The literature review shows that BOS as a source of nutrient salt and substrate for restoring seaweed grounds in an oligotrophic coastal area of Japan. The BOS contains more than 35% CaO, a potential component for CO_2 sequestration. In Japan, JFE Steel Corporation manufactured artificial reefs for seaweed/coral breeding by using carbonated steel slags. The artificial reefs show a high stability in seawater due to the fact that they consist of CaCO3, is similar to shells and coral, and act as great breeding habitats for seaweed and coral. In order to support the marine ecology, marine artificial reef structure made out of the carbonated steel slag may provide an ideal substrate to create sea forest and marine farm. Furthermore, through this integrated process of carbon dioxide mineral sequestration and carbon fixation by algal cultivation, carbon dioxide emission and waste product from the steel plant can be efficiently utilized towards sustainable development and governing the marine ecosystem restoration. The main purpose of this study is to gain an understanding effects of seaweed epiphytic and fish-gathering due to the construction of the carbonated BOS reef. An approach of carbon dioxide sequestration process by the carbonation technique and utilization as structures of artificial reefs is discussed in this paper.

II. METHODOLOGY

A. *Carbonated System of CO2 Sequestration Reactor*

The basic oxygen furnace slag (BOS) is formed during the conversion of hot metal from the blast furnace into steel in a basic oxygen furnace. BOS were collected from CSC steel plant, Kaohsiung, Taiwan. BOS main chemical compositions are CaO, SiO_2, Al_2O_3, Fe_2O_3, etc. The molten slag is cooled and solidified into basic oxygen furnace slag, which then undergoes crushing, magnetic separation, and screening to make BOFS graded aggregates.

The carbonated system of CO_2 sequestration reactor was filled with steelmaking slags (2-50 mm diameter) and freshwater medium to absorb CO_2 upon an underwater aeration plate as shown in Fig. 1. The aeration plate pumped the CO_2-rich fuel gas constantly. From the bottom to the water surface, the floating CO_2-rich bubbles drove the media to flow randomly through interspaces among the steelmaking slags. Free types of CaO and CaOH were eluted from the steelmaking slags to react with CO_2 in the media. After treating process, the steelmaking slags will be evaluated carbonation level by critical medial parameters. This novel reactor not only can sequestrate CO2, but also can reduce the alkalinity of steelmaking slags. In the carbonated system, aqueous solution of pH, CO_2 and conductivity concentration in the media of carbonation devices were examined to check carbonated condition of BOS.

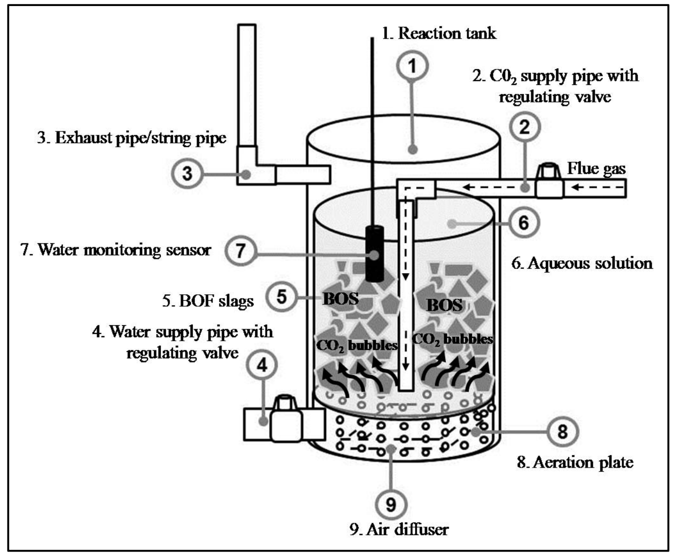

Fig. 1. Schematic diagram of carbonated system set up.

B. *Environment Safety and Bio-friendly Evaluation*

After the carbonation processes, the pH of the carbonated BOS was significantly lower (pH<10) than that of the control slag (pH=12). However, BOS contains considerable proportions of iron and silicon, which are necessary for the growth of marine algae. According to this study, marine brick of porous matrix was manufactured with the carbonated BOS to address compressive strength, JISK0058 leaching test, acute toxicity of fish, and adherence of biofouling organisms in coastal environments. In acute toxicity effects of free CaO on the euryhaline medaka (*Oryzias dancena*) test, the seawater-acclimated medaka were exposed to the seawater with the carbonated BOS with proportion of solid-liquid ratio 1:1 for 96 hrs. The results indicated that all individuals survived with healthy behaviors. Furthermore, in the culture system for macroalgae, sea grapes (*Caulpera lentillifera*) successfully attached and grew on the experimental reef of BOS. The sea grapes elongate the length, as well as increase the number of erect branches with spherical ramelli after cultivation. This study reveals that the experimental reef of calcium stones is a friendly material for seaweed cultivation.

C. *Carbon Fixation Porous Matrix and Ecological Reef*

Porous matrix and ecological reef were prepared using blast furnace cement, water and carbonated slag with the weight ratio compositions of the cement to water is 0.4 to 0.71, and the weight ratio of the carbonated BOS to the sand is 0.467 to 0.92. The design of porous matrix and reef were shown in the Fig. 2.

The carbon fixation porous matrix was provided with a plurality of carbonation basic oxygen furnace slags, a cemented material, and water. In which, the range of pH value on the carbonated basic oxygen furnace slags ranged from 6.8 to 9. The ecological reef had a recess on the top, a lower space, and at least one side opening holes. The top recess was connected with the lower space, the at least one side opening holes connect with the lower space; and the carbonated fixation porous matrix was combined into the top recess.

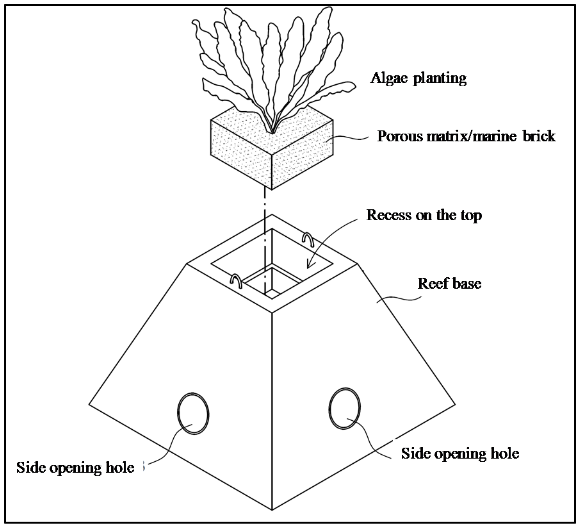

Fig. 2. Schematic diagram of porous matrix and ecological reef.

D. In-situ Deployment and Environmental Monitoring

An experiment is on trial to develop artificial reefs for marine production in the coastal area of southwestern Taiwan (Fig. 3).

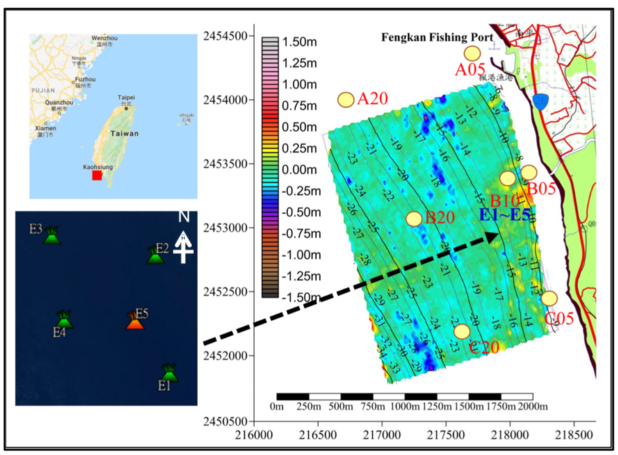

Fig. 3. Location maps of the experimental site. The positions of reefs stations (E1–E5) are shown with solid trapezoids.

In this study, we deployed five carbonated BOS of reefs (E1~E5) into a sandy bed of Fangshan coast, near Fengkan Fishing Port, Pingtung County. An experiment with artificial reefs were performed on March 13, 2017. Photograph of the prepared blocks is shown in the Fig. 4. Comprehensive marine investigation, including seasonal biological, bathymetric, tidal current, and water quality of field surveys were conducted. This study also investigated the benthic community in the sandy bed of Fangshan coastal near the Fengkan Fishing Port. The sampling site located in the south region of Fengkan Fishing Port, where was 200 meters far from the coast. Based on the result of the diving investigation, the benthic sediment was consisted of sand. The grain size of the sediment was between 0.203mm to 0.275mm, grouping to the fine sand.

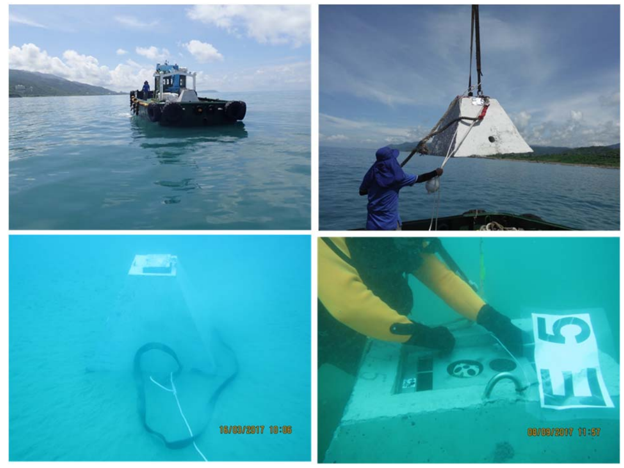

Fig. 4. Deployment of the carbonated BOS reef on the sandy seabed.

III. Results

According to the analysis of the 12 times sampling collections indicated that there were 60 families of epibenthic organisms inhabited at Fengkan coast. Nereididae was the maximum quantity of specimen, the minor one was Gammaridea. Nereididae, Portunidae and Trochidae has been captured in almost every investigation.

In comparison with artificial reef and non-reef areas has found that many fish near the reef area. On the contrary, there are few fish near non-reef area. Underwater fish finder signals display showed many fish near the reef area (Fig. 5). There are 23 species of fish had been witnessed at study sites around reefs by visual diver observations (Table I).

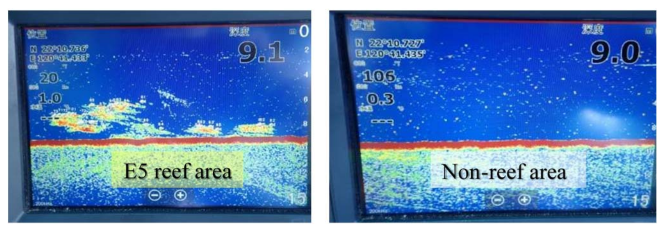

Fig. 5. Underwater fish finder signals display showed many fish near the BOS reef area during the experiment.

TABLE I. List of Bos Reef Fish Species of Study Sites by Visual Diver Observations

NO.	Fish Species		
1	*Heniochus acuminatus*	13	*Epinephelus awoara*
2	*Ostorhinchus fleurieu*	14	*Gymnothorax flavimarginatus*
3	*Ostorhinchus kiensis*	15	*Lutjanus boutton*
4	*Ostorhinchus moluccensis*	16	*Lutjanus lutjanus*
5	*Ostorhinchus novemfasciatus*	17	*Meiacanthus grammistes*
6	*Rhabdamia gracilis*	18	*Mulloidichthys flavolineatus*
7	*Pterois volitans*	19	*Neopomacentrus cyanomos*
8	*Lutjanus quinquelineatus*	20	*Paraluteres prionurus*
9	*Acanthurus maculiceps*	21	*Plectorhinchus pictus*
10	*Arothron manilensis*	22	*Dascyllus trimaculatus*
11	*Aspidontus taeniatus*	23	*Scolopsis vosmeri*
12	*Caesio caerulaurea*		

The BOS reef after 97 days of underwater testing, we found coral attached to the reef (Fig. 6). The results, as shown in Figure 6, indicate that carbonated BOS was a potential substrate for coral rehabilitation.

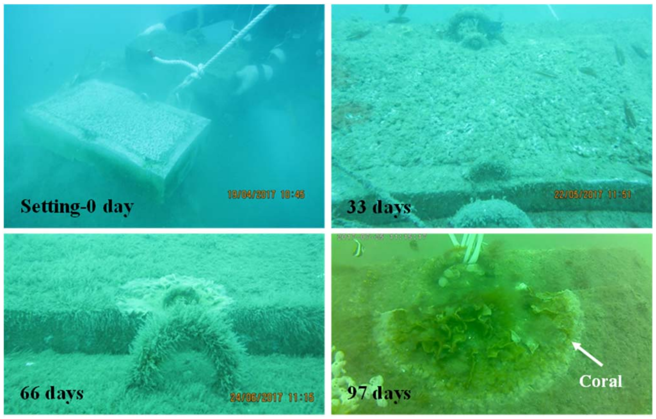

Fig. 6. Traditional diving observation showed coral attached to the reef area during the experiment.

IV. CONCLUSION

In fact, BOS reutilization channels were blocked in Taiwan for a long time. However, steel plant should still enhance self-management and control flow of BOS utilization and reversing the public misunderstanding of BOS. This study point out that the carbonation is a critical method to advances in steelmaking slags recycling and reuse.

To sum up, the carbonated BOS was suitable for the attachment growth of coral reefs. The successful development of marine brick composed of carbonated BOS could potentially offer great benefits in promoting artificial reefs function, and play an important role in marine ecosystems.

As an extension of Carbon Capture and Storage (CCS) technology, we have launched a basic research project on blue carbon (the carbon captured and sequestered by steelmaking slag and coastal ecosystems), which has started to attract attention as a measure to ameliorate the effects of climate change. We have been working on scientific interpretation of the effectiveness and safety of using carbonated BOS for the creation of sea forests. Future work will focus on the issue of from "creation of sea forests" to "blue carbon".

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