Design, fabrication, and testing of artificial reef modules

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Artificial reefs were earlier thought to be a disposal end to waste materials such as cars, boats, aeroplanes, tanks, tires, appliances, oil rigs, and demolition articles. It is often much cheaper to just dump these materials in the ocean than dispose of them in a landfill. Many of the reef structures built in the early 1900's were probably dumps to get rid of unsightly scrap materials. Then the concern among scientists increased when they realised that substances from these surplus materials might contribute to ocean pollution and destroy natural fish habitats. Materials used to make artificial reefs must be thoroughly cleaned to eliminate pollutants. They also have to be heavy enough not to be moved during storms and be made out of materials that will not corrode and collapse.

Building an artificial reef

The two major conditions that need to be satisfied before embarking on the establishment of artificial reefs along a coastal stretch are – (i) suitability of the site and (ii) suitability of the reef structure, both design, material, and mounting. Compromise in any of these conditions would result in a reversal of the favourable outcomes possible through the reef. Although artificial reefs and fish aggregating devices have been known to be used worldwide since time immemorial, the design and development of an eco-friendly reef remains a challenge

The stability and complexity of artificial reefs determine the amount of fouling (organisms attached to the substrate) and the numbers of resident species. The more complex the structure, the more diverse the resulting community will be. The spatial arrangement, number, and size of openings will determine the types and numbers of organisms present. Habitat choice is probably a determining factor of larval settlement in structuring the community but this changes over time as the reef evolves. One organism may be better adapted for a particular locale on the reef than the original pioneer species. So, until the environmental factors change, it will compete and displace the original organism and other potential inhabitants as well. This is typical of colonization of an artificial reef, due to competition and predation of the smaller individuals by fewer but larger individuals. It is also believed that smaller reefs are better at recruiting because they cover a greater horizontal space of the seafloor (Pickering 1994). In Bohnsack's 1994 study, larger reefs were found to be better for supporting fisheries while many smaller reefs promote greater diversity through recruitment. The more dispersed the reef material is, the greater the horizontal spread will be and thus, the greater the attraction capacity will be for settling organisms. The population structure in artificial reefs has been found to vary with the size of the reefs.

Therefore, the design of a reef is critical to the survival of the structure and the presence of desired species. Many different materials have been used to create artificial reefs such as tires, wood, concrete, PVC, fiberglass, plastic, metal, pulverized coal ash, and marine alloys. The use of these materials varies in different parts of the world. The following criteria are looked into for the fabrication: [1] ready availability of desirable materials, [2] matching materials to permitted reef sites, [3] avoidance of high transportation costs associated with heavy and bulky materials, [4] ease of deployment, [5] reef stability in high energy nearshore environments, [6] reduction of interference of reef structures with traditional commercial bottom fisheries, [7] longevity of reef materials, and [8] long-range cost and benefits, [9] Artificial reefs should be within easy and safe access of recreational visitors and/or fishermen.

Table 1. Purpose-specific location of artificial reefs

Purpose	Location
small boat fishermen	protected waters or within a few miles of a harbour or hamlet (within MFRA)
large boat fishermen (head or charter)	distant reefs

In Europe and Japan, the dominant material is concrete. Japan also uses steel and fiberglass. Tires are used in countries that have poor artificial reef management programs. In Australia, Jamaica, and the Philippines, tires are considered non-toxic durable materials. The United States and Europe view tires as a source of pollutant leaching, however, the United States nevertheless continues the predominant use of other materials of opportunity. There has been a serious shift worldwide towards using materials dedicated solely to the creation of artificial reefs. This allows for better designs and more effective reefs. They can be specifically designed for a single purpose such as to protect shorelines or any other of a multitude of objectives. Concrete has been found to be very favourable for artificial reef construction. It does not degrade in seawater, can be made to have neutral pH, is easily moulded and is not easily moved once in place but hard to transport to the deployment site. Concrete can be made to have a texture comparable to natural reefs and develops very similar communities as natural reefs (Pickering 1997). PVC and other plastics are also very mouldable, do not degrade, are easily transported, but are not as stable due to their lightness and are typically smooth textured. But will the structure withstand the fall to the bottom? Once in place will it withstand the stresses of currents, burial, and storms? If the reef is placed in an area of strong currents such factors as scouring must be considered along with the potential movement of the reef. Scouring under the edges of artificial reefs can result in the burial of the reef. It can also result in good burrows for cryptic species around the base of the reef. An important feature of steel is that it can be made into very complex structures. It is also very heavy and not easily moved by wave action but does corrode in seawater. Each of these materials has benefits and drawbacks.

The materials used for reef construction are to be selected with utmost caution. They must conform to the standards specified globally and nationally to ensure the quality of the seawater where the reefs are deployed. The use of hazardous materials must be avoided at all costs. In July 2022 in the United States, the Chesapeake Bay Foundation was ordered to remove all artificial reef materials from several sites in the Lynnhaven River in Virginia Beach after the reefs were found with prohibited items, such as asphalt and metal wire, sticking out of the water.

The environment of the deployment area determines the materials to be used. Artificial reefs at great depths or in protected areas with weak currents do not need to be incredibly stable. However, the greater the amount of wave action and current the more stable the reef must be to withstand having its structural integrity compromised. The seafloor's bearing capacity, compressibility and soil strength also influence the design characteristics of the artificial reef. If the ocean bottom were made of a thick layer of fine sediment a heavy reef would sink and disappear into the bottom. In this situation, lightweight reef construction materials should be used.

The shape and size of reefs also influence the physical characteristics of the surrounding area, most notably the currents around and through the reef. When an artificial reef is placed in the path of a current, it displaces the current to varying degrees depending on the porosity of the structure. In the water behind such a reef there will be a shielded locale of little or no currents (shadow-wake region). This can attract fish by giving them an area where they do not need to fight a constant current. This area may produce pressure fluctuations associated with turbulence, which can also stimulate fish aggregation. A more spread-out reef has the potential for a greater number of different niches due to a larger area covered. Reef size significantly influenced the total numbers of species, individuals, and biomass. Smaller reefs had greater fish density while larger reefs had higher biomass density from larger, but fewer, individuals. Multiple small reefs supported more individuals and more species than one large reef of equal material. Artificial reefs that were created at different times, over the course of a year, become essentially the same after they have all been in the water for at least a year. This may be because the different seasons allow different colonists to occupy the reefs. Benthic species occur in greater numbers when the reef bottom area is larger while height does not affect their numbers. Mid-level species prefer reefs with a greater vertical profile. Several studies have identified that reef size significantly influences the biomass and the total number of species and individuals, with the efficiency of artificial reefs as attractors being far greater when formed into a structure than disaggregated into pieces" (Pickering, 1996). It also follows that more complex reefs are better attractors. In a different study it was found that several smaller, but just as complex, artificial reefs have more associated individuals and species than a single larger complex reef.

Table 2. Type of reef and associated species

Type of reef	Species/resource
Low profile reefs - major sport fishery	demersal (benthic) species such as sea basses, groupers, snappers, crabs, lobsters, flounders, codfishes, tautog, rockfishes, sheepshead, seatrouts, croaker, black drum, porgies, grunts, groupers.
High-profile reefs - increase productivity	pelagic species: mackerels, jacks, bluefish, spadefishes, amberjack, tunas, barracudas, and cobia
Floating reefs	pelagic species
Combination of low and high profiles	effective for both demersal and pelagic species.

Stability over time and achievement of the expected ecological results is important to consider both the engineering aspects and the scope of the artificial reef when planning the reef units and/or the reef sets. Reef units can range from very simple modules (e.g., rocks or manmade cubes placed singly on the seabed) to sophisticated, intricately designed structures made of several different materials (e.g., steel and concrete, steel and fiberglass). Simple reef units can be assembled in reef sets to increase the three-dimensional complexity of the reef, hence enhancing its potential in the recruitment of larvae of benthic organisms and fish species. For the same scope, different typologies of reef units and/or reef sets can be used to create an artificial reef. The shape, height and weight of the reef units and reef sets are crucial for their stability and durability. It often happens that structures completely sink in muddy bottoms because they do not have a base adequate to support their weight. Complex modules may collapse due to the forces of currents and waves. Hence, the ratio of weight to surface area is crucial for the stability of the artificial reef units. Different technical project approaches are required when using modules specifically designed for artificial reefs and constructed with new or pristine materials and new sites with particular attention to the design and spatial arrangement of the structures. As a precautionary approach, structures of opportunity (tyres, ships, buses, vessels, rig pipes etc.) should not be placed close to sensitive natural habitats.

The overall objective of the production of artificial reefs is to increase the productivity of the aquatic environment and promote sustainable utilisation of the resources. When opportunely designed, artificial reefs may increase the biomass, thus increasing the availability for human consumption, of a variety of aquatic organisms (algae, molluscs, sea urchins, fish) by enhancing their survival, growth and reproduction providing them with suitable habitats and additional food. This type of artificial reef can be also used to manage the life stages of targeted species favouring aggregation of juveniles in certain areas and gathering the adults at suitable fishing grounds.

The specific applications of the production artificial reefs include:

- Recovery of depleted stocks, by increasing the survival of juveniles by providing shelter and additional food;
- Enhancement of local fisheries, by aggregating and establishing permanent populations of fish at suitable fishing grounds;
- Shifting the fishing effort from an overexploited resource to other resources; e.g., if the soft-bottom associated species in an area are overexploited, artificial reefs can serve to shift a part of the fishing effort to pelagic or reef-dwelling species;
- Compensation for a reduction of fishing effort: when there is the need for reducing the fishing effort of trawling in an area, the production of artificial reefs can be used in negotiation to create new fishing grounds allowing fishermen to shift towards more selective fishing activities;
- Development of extensive aquaculture of algae and molluscs, providing suitable substrates for settlement.

The modules generally used for production artificial reefs should be spread out, of various shapes, and should have an appropriate amount of surface area and niches of various shapes and sizes available for the establishment of settling organisms. Differently from the protection reef units, production units have usually more volume to their weight, creating three-dimensional complexity and developing surfaces which can be colonised by sessile organisms. Rough surface texture enhances benthic settlement providing refuge and supporting greater diversity. Consequently, it also affects the fish assemblage attracting fish grazing.

Besides food availability, composition, diversity and abundance of the reef, fishes are strongly affected by the occurrence of adequate refuges and by the shape of the structures. Habitat quality affects habitat selection by fish and consequently, influences the demography and population dynamics of the reef fish assemblage. Hence, to host a permanent community, an artificial reef must provide adequate habitats for juveniles and adults. Based on the fractal crevices theory in structurally complex natural or artificial environments large crevices are much rarer than smaller ones. Consequently, the artificial reefs can host more small and medium-sized than large organisms which tend to migrate outside. Therefore, the placement of large-holed reef units (especially in marine protected areas) could avoid the depletion of broodstock by fishing and enhance the reproductive capacity of reef fish.

Other factors that should be considered in planning the artificial reef structures are:

- independent of the size and the life stage, generally fish prefer cavities where there is light and with many openings to enable them to escape from predators;
- size, number, and orientation of cavities should match with the behavioural features of the target species, such as whether they are territorial or gregarious;
- the overall design of artificial reef structures should assure adequate water circulation. Regarding the shape of the reef units/reef sets, it is well known that the affinity of several aquatic organisms towards the artificial substrates varies widely depending on the species and the life stage. Because of this, when constructing a reef for fisheries enhancement, it is important to deeply know the ecology of the different species to identify those that are more appropriate as targets for artificial reef deployment and that will have a higher probability of being manageable through manipulations involving artificial reefs.

CMFRI has been experimenting with several designs which include –

- Concrete rings
- Old tyres/fixed on a concrete bed
- Triangular or rectangular modules with PVC or stoneware pipes fitted inside
- HDPE pipe structures
- Rectangular box-like Circular (dense)
- Tetrapod
- Triangular modules (130 kg) 5 feet height units
- **MOU** with **Intermediate Technology Development Group, London and the Southampton University (1995) -** design of 5 feet triangular fish reef module took place (120 kg) and so was the module placement technique engaging the traditional crafts at Trivandrum.
- **Concrete Artificial Reef Modules-particulars**

Three types of artificial reef modules developed by CMFRI are Grouper Fish Module (GFM), Reef Fish Module (RFM) and Well Ring Module (WRM) and three-generational modifications have been adopted over a period of time, based on field trials and observations. Since the development of the standard modules for three classes of fishes (Reef fishes-Trevallies-breams-perches **Triangular/pyramid module**, Benthic crustacean fauna -**Well ring or flower module** and the cods-groupers-eel- **Tubular Pipe module [Patent 197/CHE/2012]** "Cement and concrete moulded artificial reef to aggregate marine fish") three generations of designs and sizes have evolved based on the observations in performances, stability, shelf life, compatibility with the fishing gears and substratum and the dynamics of the seabed and reef fish built-up efficiency.

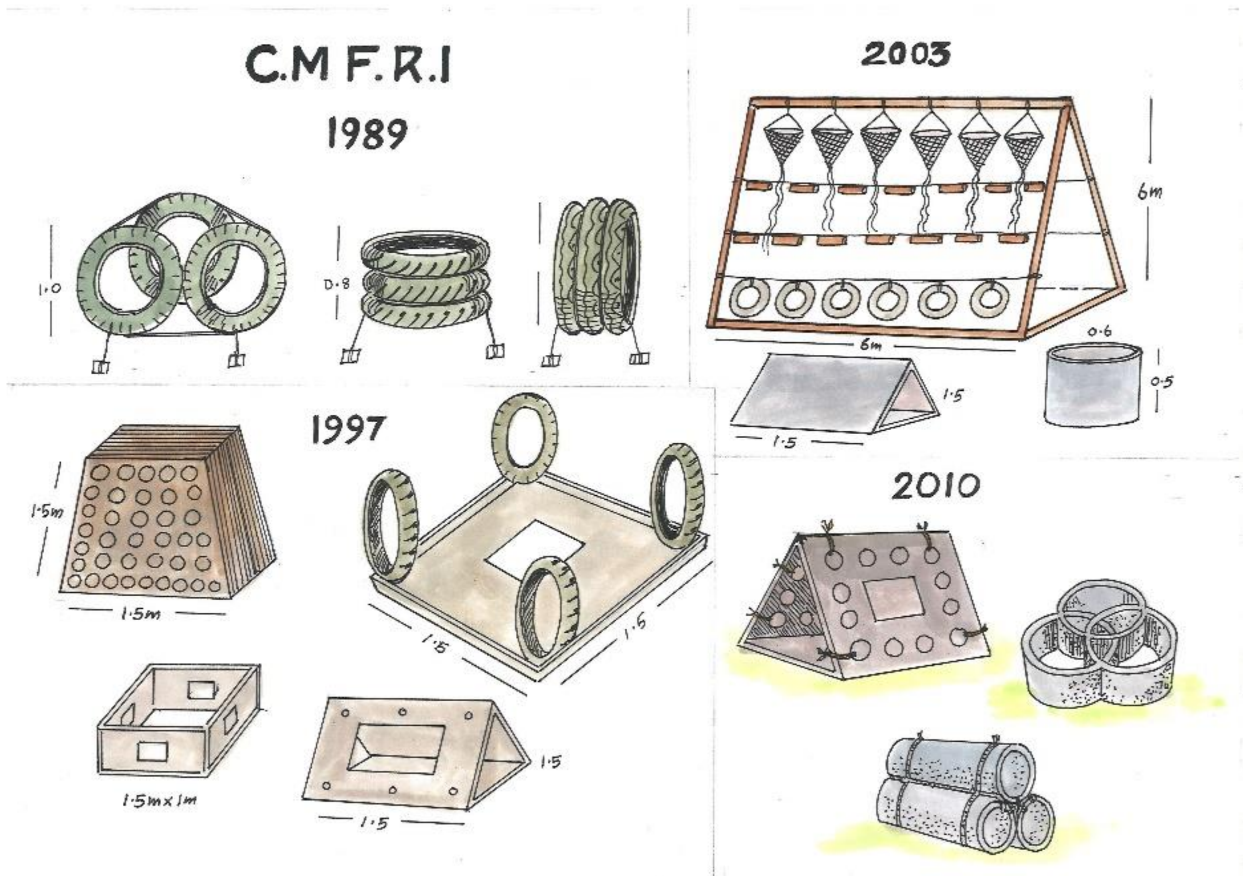

Fig.9. Different designs of AR Modules trailed by CMFRI

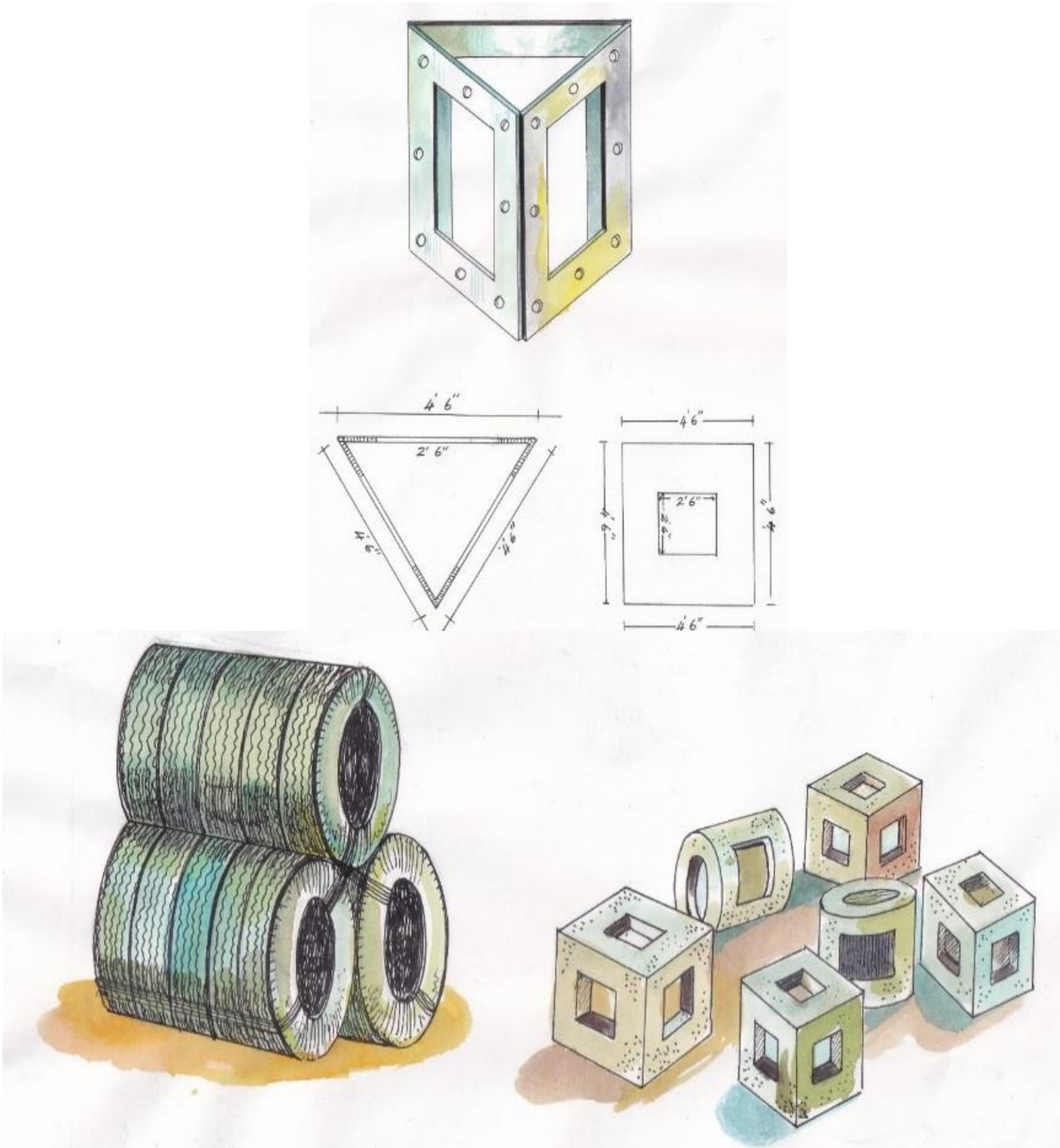

Fig.10. Earlier designs of AR Modules trailed by CMFRI

Generation A. 2009

Grouper Fish Module (GFM)

6 mm MS reinforced, with concrete (RCC) pipes (3 nos.) 280 mm ID 410 mm OD dia x 1000mm length, fixed and plastered and housed inside the triangular slab structure (1m x 1 m x 1 m), cured. The concrete and mortar of the best standards to be provided

Reef Fish Module (RFM)

6 mm MS reinforced, Triangular moulded concrete module (1.2 m x 1.2 m x 3 slabs of 2.5-inch thickness). Each slab has 0.23 x 0.23 m square opening in the centre & amp; 0.15 m dia circular holes surrounding the central square opening (12 nos. / slab)

Well Ring Module (WRM)

6 mm rod reinforced concrete Well Ring (overlapping) Module; 0.76 mm dia rings (3), 0.450 mm depth, 65 mm thick

Note: Concrete 1:1:2 ratio, 5mm baby jelly, stucco plastering and coarse sand and blue metal layering on the surface plastering (rough cast plastering).

2 weeks curing for all the above modules with fresh water

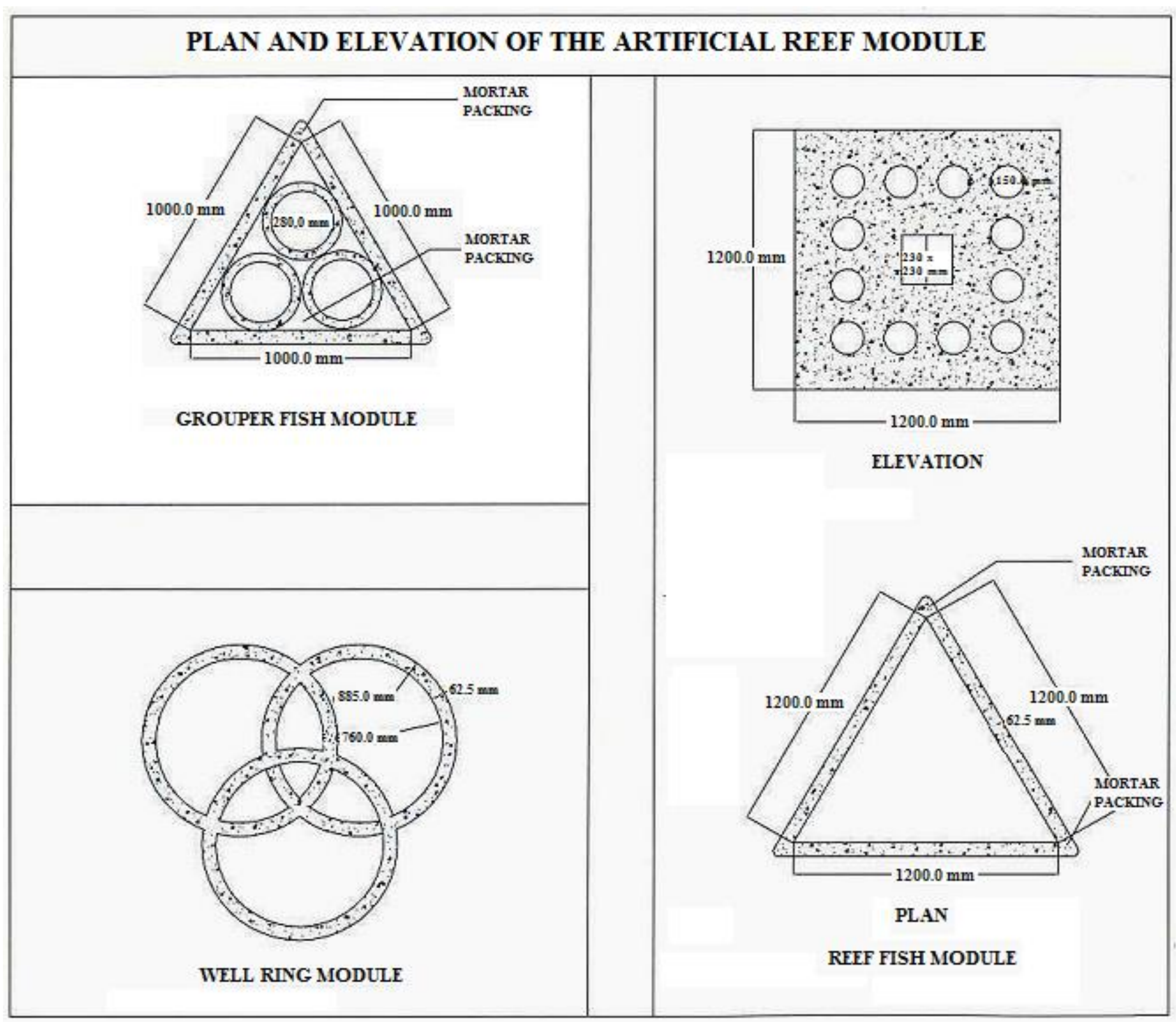

Fig.11. Dimensions of different reef modules

Generation B. 2012-2015

A. Grouper fish module (GFM)

1000 mm L X 300 mm ID (430 mm OD), 65 mm thickness, 6 mm MS rod
3 pipes held 20 mm by HDPE rope and loop for lifting
Rough cast plastering, 5 mm baby jelly

B. Well ring module (WRM)

760 mm ID, 890 mm OD, 450 mm depth, 6 mm MS rod
20 mm HDPE rope and loop for lifting
Rough cast plastering, 5 mm baby jelly

C. Reef fish module (RFM)

1200 x 1200 mm 3 slabs**,** 6 mm MS rod
mortar packed corners into a triangular hut, rough cast plastering, 5 mm baby jelly
20mm HDPE rope and loop for lifting
65 mm thickness, rough cast plastering
Each slab has a central window 230x230mm and 12 peripheral holes 0f 150 mm dia.

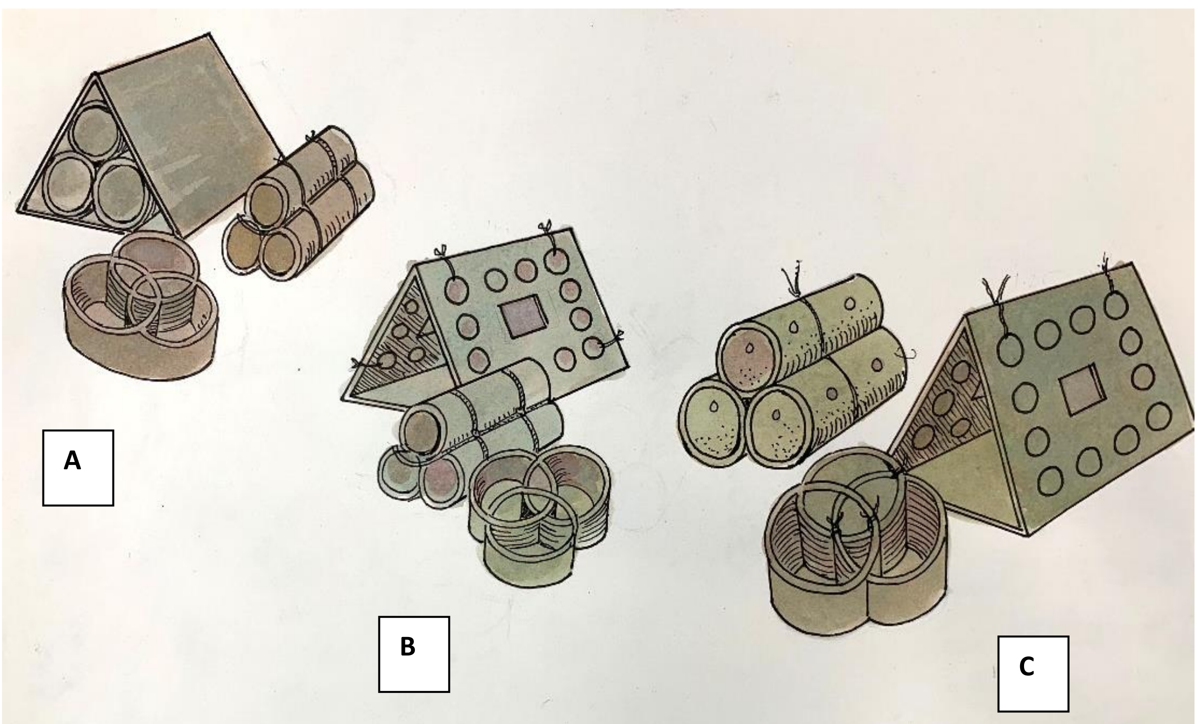

Fig.12. A – Module type I (150 nos.); B- Module Type II (150-175 nos.) & C- Module type III (200-275 nos.)

Two weeks of curing with fresh water is required for all the above modules.

Generation C. 2016

D. Grouper fish module (GFM)

1000 mm L X 300 mm ID (450 mm OD),75 mm thickness, 8 mm RDS rod
Fused pipes with holes coir loop for lifting
Stucco 12 mm plastering, 10 mm baby jelly

E. Well ring module (WRM)

760 mm ID, 890 mm OD, 450 mm depth, 8 mm RDS rod, 75 mm thickness
20 mm COIR rope and loop for lifting
Stucco 12 mm plastering, 10 mm baby jelly

F. Reef fish module (RFM)

1200x 1200 mm 3 slabs**,** 8 mm RDS rod, 75 mm thickness
mortar packed corners into a triangular hut, Stucco 12 mm plastering, 10 mm baby jelly
20 mm coir rope and loop for lifting
Each slab has a central window 230x230 mm and 12 peripheral holes of 150 mm dia.
Reinforced cement concrete of M30 (OPC)43 gradeIS8112 as per BIS-456-200 (440 Kg/M3) using 20 mm and 12 mm gauge HBG stone jelly. With water cement ratio 0.45 and super plasticizer 250 ml/50 kg cement. Stucco plastering 12 mm HBG chips of 10 mm CM 1:5 mix x 12 mm thick.
The recent versions are treated and cured for 3 weeks with freshwater and seawater for a week before the deployment.

Fabrication at the site, inspection and verification

During the evaluation and testing of the modules, it is imperative that -

- The dimensions and concrete mixture are to be checked
- The rod sizes, curing period and the stucco plastering thickness
- The cement grade and the plasticizer
- The strength and durability are to be tested between 7-28 days of fabrication.
- (Fineness Test., Consistency Test., Setting Time Test. Strength Test., Soundness Test., Heat of Hydration Test., Tensile Strength Test., Chemical Composition Test.)
- The modules are numbered and arranged for easy shipment and loading.
- The modules are to be weighed on a weighing scale and the GRT per trip per site has to be evaluated for port bills and clearances at harbours.

Fig.13. The latest AR modules being deployed by CMFRI

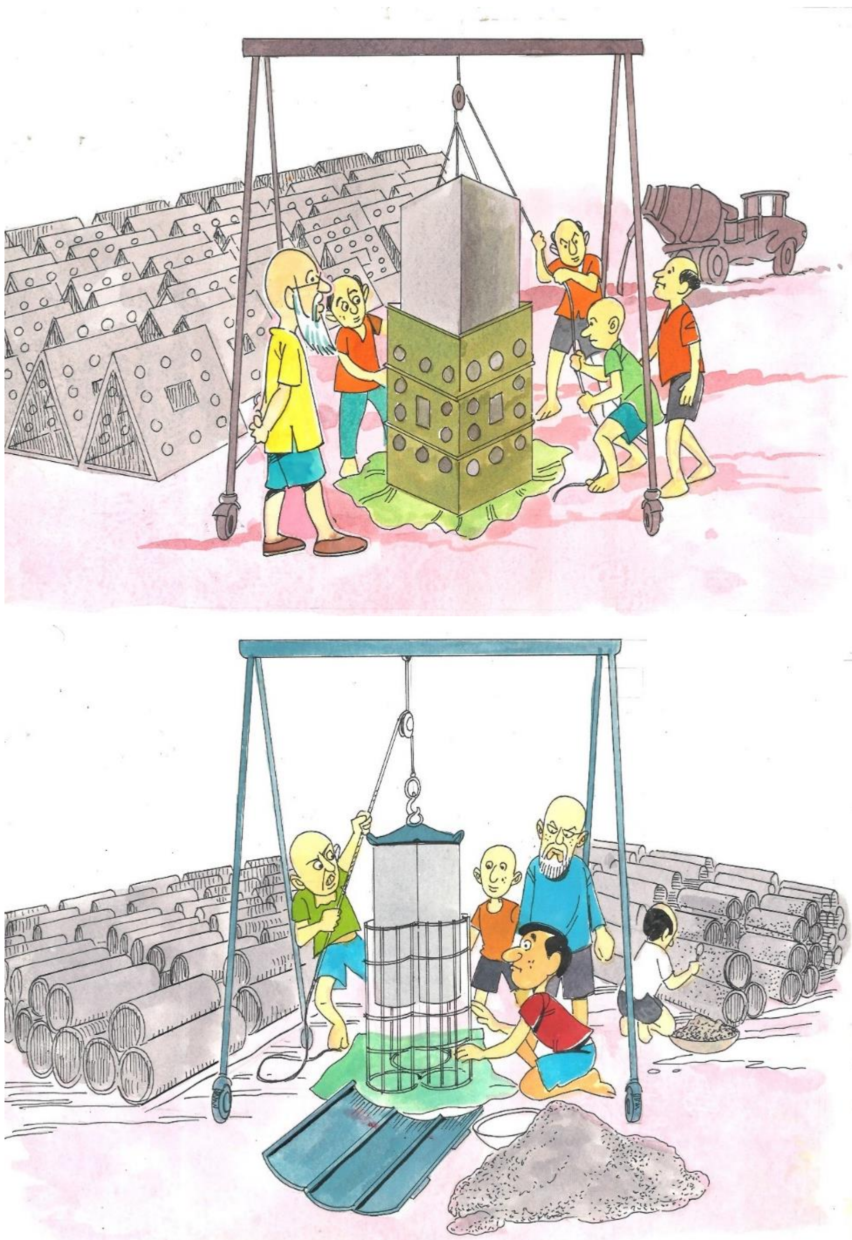

Fig.14. Fabrication of AR Modules

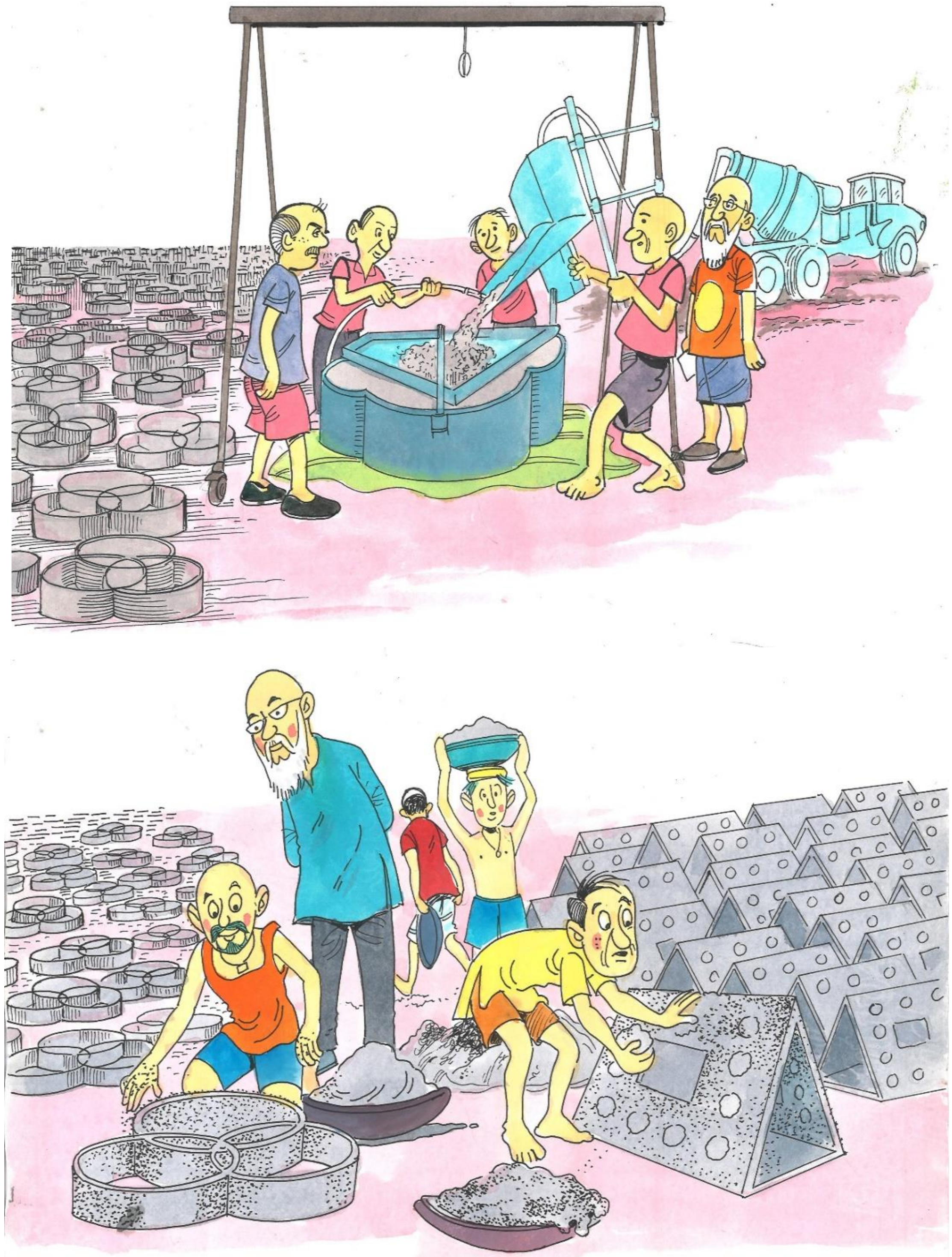

Fig.15. Fabrication of AR Modules

Table 3. The evolution of artificial reef modules developed by ICAR-CMFRI, with their dimensions and constitution

S. no.	Name of the model	Sizes LxBxH	Thickness	Stucco/ Rod	Additional remarks	Fishery resource	Weights	Functions
1	GEN. I REEF - PYRAMID FISH MODULE	1.2 m x 1.2 m x 3 slabs	63.5 mm	Concrete 1:1:2, 6 mm MS	Rough cast plastering 5 mm baby jelly	Snappers, perches,	250-350 kg	Shelter and attract forage fishes, house benthic forms, production units
2	G. I GROUPER FISH MODULE	Encased inside slabs on all sides, 280 mm ID 410 mm OD dia x 1000 mm length	63.5 mm	Concrete 1:1:2, 6 mm MS	Rough cast plastering 5 mm baby jelly	Groupers, eel, perches	400 kg	Home for big predators and keeps the mobility of fish in ease and develop corridors
3	G. I (WRM)WELL RING - FLOWER MODULES	0.76 mm dia rings (3), 0.450 mm depth, 65 mm thick	63.5 mm	Concrete 1:1:2, 6 mm MS	Rough cast plastering 5 mm baby jelly	Crustaceans, gobiids, wrasses, cardinals	350-450 kg	Stoppers in the sediment, secure platform and chambers, crustacean recruit houses, production units
4	GEN. II REEF - PYRAMID FISH MODULE	1.2 m x 1.2 m x 3 slabs	63.5 mm	Concrete 1:1:2, 6 mm MS	HDPE ROPE 18 mm	Snappers, perches, damsels, zanclids, Lions fishes, Wrasses, rabbits, surgeons, corals	500-550 kg	Shelter and attract forage fishes, house benthic forms, production units
5	G. II GROUPER FISH MODULE	300 mm ID 430 mm OD dia x 1000 mm length	63.5 mm	Concrete 1:1:2, 6 mm MS	HDPE ROPE 18 mm	Groupers, snappers, sea bass, damsels, eels, sweet lips, grunters,	650-750 kg	Home for big predators, and keeps the mobility of fish in ease and develop corridors
6	G. II (WRM) WELL RING- FLOWER MODULE	0.76 mm dia rings (3), 0.450 mm depth	63.5mm	Concrete 1:1:2, 6 mm MS	HDPE ROPE 18 mm	Cardinals, crustaceans, lobsters, sea lilies, corals,	550-650 kg	Stoppers in the sediment, secure platform and chambers, crustacean recruit

								houses, production units
7	GEN. III REEF - PYRAMID FISH MODULE	1200x 1200 mm 3 slabs	75 mm	MP 9OPC) 43 GRADE IS 112 BIS-456-200 (440 kg/m^3) 20 mm and 12 mm HGB stone jelly	20 mm COIR ROPE	Snappers, perches, damsels, zanclids, lion fishes, wrasses, rabbits, surgeons, trevallies, breams, corals, groupers, rabbits, squirrels	650-750 kg	Shelter and attract forage fishes, house benthic forms, heavy and hence creates more wake regions, increased substratum
8	G. III GROUPER FISH MODULE	1000 mm L X 300 mm ID (450 mm OD)	75 mm	MP 9OPC) 43 GRADE IS112 BIS-456-200(440KG /M3) 20mm and 12mm HGB stone jelly	20 mm COIR ROPE	Groupers, snappers, sea bass, damsels, eels, sweet lips, grunters	800-900kg	Home for big predators, and keeps the mobility of fish at ease and develop corridors
9	G. III (WRM) WELL RING -FLOWER MODULE	760 mm ID, 890 mm OD, 450 mm depth	75 mm	MP 9OPC) 43 GRADE IS 112 BIS-456-200 (440 kg/m^3) 20 mm and 12 mm HGB stone jelly	20 mm COIR ROPE	Cardinals, crustaceans, lobsters, sea lilies, corals, goat fishes, clowns, wrasses,	650-800 kg	Stoppers in the sediment, secure platform, and chambers, transplanting spaces, crustacean and cardinals, damsel and ornamental recruit houses, production units