ARTIFICIAL REEF MATERIALS

Preliminary study of the potential for the development of ”Macroalgae reefs” in the Limfjorden.

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Contents

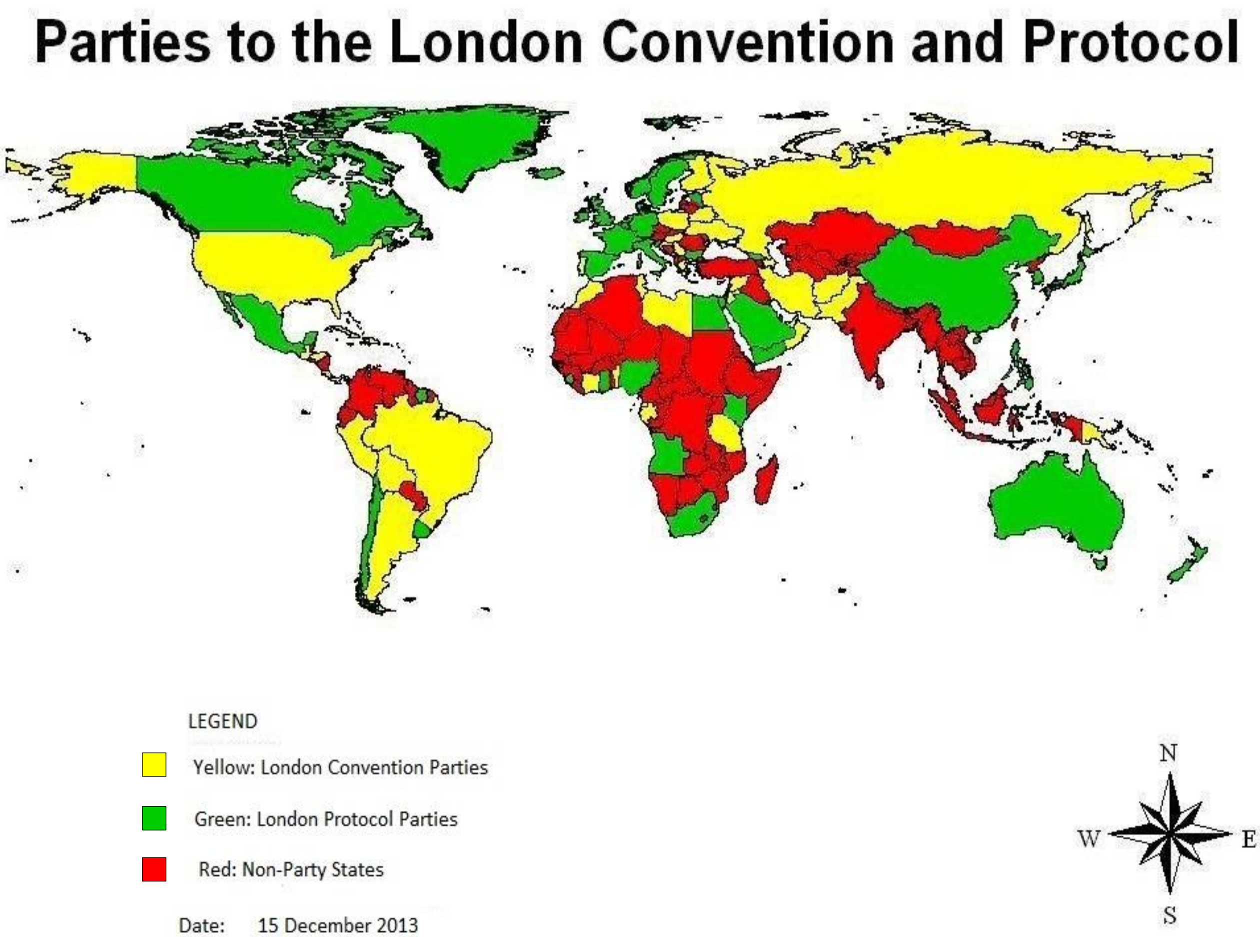
London Protocol

1. Definition and contracting parties

The "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972", the "London Convention" in short, is one of the first global conventions to protect the marine environment from human activities and has been in force since 1975. Its objective is to promote the effective control of all sources of marine pollution and to take all practicable steps to prevent pollution of the sea by dumping of wastes and other materials. Currently, 87 States are Parties to this Convention.

In 1996, the "London Protocol" was agreed to further modernize the Convention and, eventually, replace it. Under the Protocol all dumping is prohibited, except for possibly acceptable wastes on the so-called "reverse list". The Protocol was reinforced on 24 March 2006 and there are currently 45 Parties to the Protocol. The Parties of this protocol are the one on green of the following image.

Despite the fact that building an artificial reef should not be considered as a waste dumping we will confirm, anyways, that the materials that would be used can meet the London's protocol standards.



2. Regulation about dumping

The following text was extracted from the London Protocol (2006).

ANNEX 1

WASTES OR OTHER MATTER THAT MAY BE CONSIDERED FOR DUMPING

1 The following wastes or other matter are those that may be considered for dumping being mindful of the Objectives and General Obligations of this Protocol set out in articles 2 and 3:

.1 dredged material;

.2 sewage sludge;

.3 fish waste, or material resulting from industrial fish processing operations;

.4 vessels and platforms or other man-made structures at sea;

.5 inert, inorganic geological material;

.6 organic material of natural origin;

.7 bulky items primarily comprising iron, steel, concrete and similarly unharmful materials for which the concern is physical impact, and limited to those circumstances where such wastes are generated at locations, such as small islands with isolated communities, having no practicable access to disposal options other than dumping; and

.8 Carbon dioxide streams from carbon dioxide capture processes for sequestration.

2 The wastes or other matter listed in paragraphs 1.4 and 1.7 may be considered for dumping, provided that material capable of creating floating debris or otherwise contributing to pollution of the marine environment has been removed to the maximum extent and provided that the material dumped poses no serious obstacle to fishing or navigation.

3 Notwithstanding the above, materials listed in paragraphs 1.1 to **1.8** containing levels of radioactivity greater than *de minimis* (exempt) concentrations as defined by the IAEA and adopted by Contracting Parties, shall not be considered eligible for dumping; provided further that within 25 years of 20 February 1994, and at each 25 year interval thereafter, Contracting Parties shall complete a scientific study relating to all radioactive wastes and other radioactive matter other than high level wastes or matter, taking into account such other factors as Contracting Parties consider appropriate and shall review the prohibition on dumping of such substances in accordance with the procedures set forth in article 22.

3. Viability of possible materials

To study the viability of the available materials we must know if they meet with the standards of London Protocol. The below listed materials are specifically selected for reef building, differing in some cases from the standardized materials (for example "Concrete" is not the typically-used construction concrete, but a specific concrete)

Material	Dredged	Sewage Sludge	Fish waste	Man-made structures at sea	Inert, inorganic geological material*	Organic or natural origin material	Bulky items that don't have access to disposal	Carbon dioxide streams
Concrete	X	X	X	X	√	X	X	X
Iron	X	X	X	X	X	X	X	X
Wood	X	X	X	X	X	√	X	X
Blue mussel Cement	X	X	√	X	X	√	X	X
Reinforced concrete	X	X	X	X	X	X	X	X
Boulders		X	X	X	√	X	X	X
Fiberglass	X	X	X	X	X	X	X	X
Plastics	X	X	X	X	X	X	X	X

* To determine whether a material is inert, inorganic, geological, must comply with the following table below.

Characteristics of the inert, inorganic and geological materials	Geological Mat.	Inert Mat.	Inorganic Mat.	Concrete	Iron	Wood	Blue mussel Cement	Reinforced concrete	Boulders	Fiberglass	Plastics
It is made exclusively with Earth´s solid layer materials	√	-	-	√	√	X	√	√	√	X	X
It has been altered from its original form by physical or chemical process so that it has a different or an additional impact on the marine environment	X	-	-	X	X	X	X	√	X	√	√
Once at sea, the only possible alterations are physical (not chemical or biological)	-	√	-	√	X	X	√	X	√	√	√
It is an inorganic mineral material	-	-	√	√	√	X	√	√	√	X	X
The amount of carbohydrate-based compounds is negligible	-	-	√	√	√	X	√	√	√	X	X
Inert, inorganic and geological material				√	X	X	√	X	√	X	X

Concrete

1. Composition

Concrete is a material composed mainly of **cement**, **water** and **aggregates**. Usually there are additives and reinforcements included to achieve the desired physical properties of the finished material.

- **Portland cement** is the most common type of cement in general usage. It consists of a mixture of oxides of calcium (Ca), silicon (Si) and aluminum (Al). Portland cement and similar materials are made by heating limestone (a source of calcium) with clay and grinding this product (called clinker) with a source of sulfate (most commonly gypsum).
- Combining **water** with cement powder forms a cement paste by the process of hydration. The cement paste glues the aggregates together, fills voids within it, and makes it flow more freely. A lower water-to-cement ratio yields a stronger, more durable concrete, whereas more water gives a freer-flowing concrete with a higher slump. Impure water used to make concrete can cause problems when setting or in causing premature failure of the structure. The balanced reaction is:

$$2Ca_3SiO_5 + 7H_2O \rightarrow 3(CaO)\cdot 2(SiO_2)\cdot 4(H_2O)(gel) + 3Ca(OH)_2$$

- Fine and coarse **aggregates** make up the bulk of a concrete mixture:
    - Sand, natural gravel and crushed stone are used mainly for this purpose.
    - Recycled aggregates (from construction, demolition, and excavation waste).

There is also a way to make the concrete a more **ecofriendly material**. It is by using **Pozzolanic cement**. Pozzolanic cement is a hydraulic binder produced from the mixture of a material known as pozzolana and finely ground Calcium Hydrate. This binder is of low mechanical strength and its setting speed is a little bit slower than Portland cement. Therefore, it can be considered as cement for masonry applications. Pozzolans are siliceous or aluminum-siliceous materials that can be extracted artificial or naturally:

- **Artificial pozzolans:**
    - Flying ashes: the ashes produced during the mineral carbon combustion (lignite), mainly in thermal plants that generate electricity.
    - Activated or artificially burnt clays: for example, residues from burning clay bricks as well as other types of clays subjected to temperatures higher than 800 °C.
    - Slags: mainly from ferrous alloys in blast furnaces. These slags must be violently cooled so that they an amorphous structure can be formed.
    - Ashes from agricultural residues: rice shell ash, bagasse ash and sugar cane straw. When conveniently burnt, a mineral residue rich in silica and alumina, whose structure depends on the combustion temperature, is obtained.

- **Natural pozzolans:**
  - Volcanic rocks, in which the amorphous constituent is glass produced from the sudden cooling of lava. For example, volcanic ashes, pumice, tufa, slags and obsidian. Rocks or soils in which the siliceous constituent contains opal, either by siliceous precipitation from a solution or from the residues of organisms, such as diatom earths or clays naturally calcinated from the action of heat or from a lava flow.

The pozzolanic reaction is the chemical reaction that occurs in Portland cement containing pozzolans:

$$Ca(OH)_2 + H_4SiO_4 \rightarrow Ca^{2+} + H_2SiO_4^{2-} + 2\ H_2O \rightarrow CaH_2SiO_4 \cdot 2\ H_2O$$

2. Production

The production of the concrete involves next steps:

- **Production of cement:**
  - **Portland cement:** is made by heating limestone (calcium carbonate) with small quantities of other materials (such as clay) to 1450 °C in an oven, in a process known as calcination, whereby a molecule of carbon dioxide is liberated from the calcium carbonate to form calcium oxide, or quicklime, which is then blended with the other materials that have been included in the mix. The resulting hard substance, called 'clinker', is then ground with a small amount of gypsum into a powder to make 'Ordinary Portland Cement'.
  - **Portland Pozzolanic cement:** is the product resulting from the addition of pozzolanic material to normal Portland cement, in a percentage of 15 to 50%. Such attachment may be effected in the state of clinker, in order to be ground together (with appropriate fineness).
  - **Pozzolanic cement CP40:** is produced from a mixture of very fine lime hydrate and Pozzolana powders with an average proportion of 70% Pozzolana and 30% lime. The material obtained demands a fineness similar to that of common Portland cement (250-300 m^2/kg Blaine Test).

- **Mixing of the cement, water and aggregates:**

  Thorough mixing is essential for the production of uniform, high-quality concrete. For this reason equipment and methods should be capable of effectively mixing concrete materials containing the largest specified aggregate to produce uniform mixtures of the lowest slump practical for the work. Separate paste mixing has shown that the mixing of cement and water into a paste before combining these materials with aggregates can increase the compressive strength of the resulting concrete. The paste is generally mixed in a high-speed, shear-type mixer at a w/cm (water to cement ratio) of 0.30 to 0.45 by mass.

- **Curing of the concrete:**

  This happens after the concrete has been placed. Cement requires a moist, controlled environment to gain strength and harden fully. The cement paste hardens over time, initially setting and becoming rigid though very weak and gaining in strength in the weeks following. In around 4 weeks, typically over 90% of the final strength is reached, though strengthening may continue for decades. Hydration and hardening of concrete during the first three days is critical. In practice, this is achieved by spraying or ponding the concrete surface with water, thereby protecting the concrete mass from ill effects of ambient conditions.

In addition, the concrete that would be used for building on the seabed needs to meet the following characteristics:

- Low content of tricalcium aluminate ($Ca_3Al_2O_6$, or $3CaO \cdot Al_2O_3$), it must be under 8%.
- Additives should be banned.
- The characteristic strength of concrete will not be less than 19.62 MPa (200 kg / cm^2).
- It is recommended a dosage not below 350 Kg of cement/m^3.
- It is recommended a maximum size of 20 mm for aggregate.
- It is recommended the use of pozzolanic cements as type IV or II-Z of the UNE-80-301:

DESIGNACIÓN	UNE 80 301 88		ENV 197-1	
	Tipo	Composición	Tipo	Composición
Cemento puzolánico	IV	Z Puzolana natural C Ceniza volante ≥ 60 % Clínker ≤ 40 % Z, C 0-5 % Adición	IV/A IV/B	65-90 % Clínker 10-35 % D, P, Q, V 0-5 % Adición 45-64 % Clínker 36-55 % D, P, Q, V 0-5 % Adición
Portland con puzolana	II-Z	72-94 % Clínker 6-28 % Z 0-5 % Adición	II/A-P II/A-Q II/B-P II/B-Q	80-94 % Clínker 6-20 % P, Q 0-5 % Adición 65-79 % Clínker 21-35 % P, Q 0-5 % Adición

3. Characteristics

3.1. Structural behavior

Concrete has a high compressive strength, but significantly lower tensile strength. The elasticity of concrete is relatively constant at low stress levels. Concrete has a very low coefficient of thermal expansion, and as it matures concrete shrinks.

It is usually required the compressive strength of concrete, which is normally given as the 28 day compressive strength. A 25% strength gain between 7 and 28 days is often observed with 100% ordinary Portland cement mixtures, and between 25% and 40% strength gain can be realized with the inclusion of pozzolans and supplementary cementitious materials such as fly ash and/or slag cement.

Typical properties of normal strength Portland Cement concrete are indicated below:

Density	2240 - 2400 kg/m^3	**Drying shrinkage**	4 - 8 x 10^{-4}
Flexural strength	3 - 5 MPa	**Permeability**	1 x 10^{-10} cm/sec
Modulus of elasticity	14000 - 41000 MPa	**Coefficient of thermal expansion**	10-5 $^{o}C^{-1}$
Compressive strength	20 - 40 MPa		
Shear strength	6 - 17 MPa	**Poisson's ratio**	0.20 - 0.21
Tensile strength	2 - 5 MPa	**Specific heat capacity**	0.75 kJ/kg K

3.2. Durability

One of the major advantages of use of pozzolanic materials in concrete mixes is to improve the durability of concrete. The existence of large pores and large crystalline products in the transition zone in ordinary Portland concrete are greatly reduced by the introduction of fine particles of pozzolanic materials. The decrease in the pore interconnectivity of concrete thus decreases the permeability of blended concrete. The reduced permeability results in improved long term durability and resistance to various forms of deterioration of concrete structures.

The operational lifetime depends on the water conditions of the Limfjorden and the characteristics of the final blend of the concrete used, but it is usually more than 50 years on conventional concretes for structural use. Therefore, it would be expected a longer lifetime since the artificial reef will have no structural loads.

The following chart is an extract of **Reliability Approach to Service Life Prediction of Concrete Exposed to Marine Environments** (Monica Prezzi, Philippe Geyskens, and Paulo J. M. Monteiro, 1996) in which it is calculated the expected lifetime of different mixes of reinforced concrete exposed to marine environment. This lifetime is defined as the time for corrosion initiation of the reinforcement bars at 5cm inside the concrete.

Table 4—Time in years necessary for threshold chloride concentration to be reached at reinforcement* with 50 percent probability

Mix	$0.2\ C_{total}$	$0.25\ C_{total}$	$0.3\ C_{total}$	$0.35\ C_{total}$	$0.4\ C_{total}$
1	70	68	67	65	63
2	65	63	62	60	58
3	47	46	45	44	43
4	36	33	31	28	25
5	57	57	57	56	55
6	66	66	65	64	62
7	51	51	50	52	47
8	43	42	41	39	37
9	48	56	46	44	42
10	37	35	33	31	29

*Cover thickness 5 cm (1.97 in.).

Assuming no chloride binding or adsorption and 100 percent saturation, the chloride content profiles obtained from laboratory tests such as the immersion test can be transformed to chloride concentration profiles using the following conversion equation:

$$C = \frac{C_{dry\ concrete} \times \gamma_{dry\ concrete}}{\rho \times n}$$

where C (percent) is the chloride concentration per weight of water.

In the Second Edition of the **GUIDELINES FOR MARINE ARTIFICIAL REEF MATERIALS (2004) Compiled by the Artificial Reef Subcommittees of the Atlantic and Gulf States Marine Fisheries Commissions** it is said that *"Other studies have tested strength of concrete in seawater over a 30-50 year period. In all tests, concrete of various types continued to gain compressive strength which continued to increase over the period of observation" (Portland Cement Association, personal communication). This increase in strength is due to the continuing hydration of the cement on a molecular level. The duration of these studies has not been sufficient to measure how long this strengthening process may continue, but estimates range from many decades to hundreds of years.*

In fact, hydraulic pozzolanic concretes (first developed by the Romans in second century BCE) were widely used in important harbor constructions along the Mediterranean seacoast, over several centuries. Between 2002 and 2009, the ROMACONS group drilled Roman maritime concretes in 11 harbors. These structures have remained cohesive and intact in the seawater environment for 2,000 years **[2012, Cement Microstructures and Durability in Ancient Roman Seawater Concretes, Marie D. Jackson et al.]**.

So, in summary, we can predict a lifetime in service of the concrete higher than 50 years (according to the foregoing).

3.3. Environmental behavior

Concrete exposed to seawater is susceptible to its corrosive effects. The effects are more pronounced above the tidal zone than where the concrete is permanently submerged. In the submerged zone, magnesium and hydrogen carbonate ions precipitate a layer of brucite ($Mg(OH)_2$), about 30 micrometers thick, on which a slower deposition of calcium carbonate as aragonite occurs. These layers somewhat protect the concrete from other processes, which include attack by magnesium, chloride and sulfate ions and carbonation.

Above the water surface, mechanical damage may occur by erosion by waves themselves or sand and gravel they carry, and by crystallization of salts from water soaking into the concrete pores and then drying up.

Pozzolanic cements and cements using more than 60% of slag as aggregate are more resistant to sea water than pure Portland cement. Sea water corrosion contains elements of both chloride and sulfate corrosion.

- Chlorides, particularly calcium chloride ($CaCl_2$), have been used to shorten the setting time of concrete. However, calcium chloride and, to a lesser extent, sodium chloride (NaCl) have been shown to leach calcium hydroxide ($Ca(OH)_2$) and cause chemical changes in Portland cement, leading to loss of strength.

- Sulfates in solution in contact with concrete can cause chemical changes to the cement, which can cause significant microstructural effects leading to the weakening of the cement binder (chemical sulfate attack). Sulfates and sulfites are abundant in the natural environment and are present from many sources, including gypsum (calcium sulfate) often present as an additive in 'blended' cements which include fly ash and other sources of sulfate.

The cement industry is one of two primary industrial producers of carbon dioxide (CO_2), creating up to 5% of worldwide man-made emissions of this gas, of which 50% is from the chemical process and 40% from burning fuel. The CO_2 produced for the manufacture of one ton of structural concrete (using ~14% cement) is estimated at 410 kg/m^3 (~180 kg/ton with a density of 2.3 g/cm^3). But it is reduced to 290 kg/m3 (127,32 Kg/ton) with 30% fly ash replacement of cement. The CO_2 emission from the concrete production is directly proportional to the cement content used in the concrete mix. About 900 kg of CO_2 are emitted for the fabrication of every ton of cement.

Cement manufacture contributes greenhouse gases both directly through the production of carbon dioxide when calcium carbonate is thermally decomposed, producing lime and carbon dioxide, and also through the use of energy, particularly from the combustion of fossil fuels.

4. Advantages and disadvantages as reef material

Advantages	Disadvantages
• Concrete materials are perfectly compatible with the marine environment. • Concrete is highly durable, stable and readily available. • The flexibility to mold the concrete in a wide range of shapes makes it ideal for the development of prefabricated units. • Concrete provides a suitable habitat for colonization and growth of fouling organisms, which also provide substrate and shelter for fish and other invertebrates. • Can be produced *in situ*.	• Concrete is heavy, so the use of heavy equipment is required to manipulate it, which increases the cost of land and sea transport. • The installation of large blocks or precast concrete units requires the use of heavy marine equipment, which is not only costly, but also dangerous. • Its weight increases the chances to break during the placement. • The high carbon footprint derived from the production of cement and aggregates needed.

Blue Mussel Concrete

1. Composition

The idea of Blue Mussel Concrete is extracting the calcium carbonate ($CaCO_3$) needed for the cement, from the shell of the blue mussels. So the composition would be the same as the normal concrete explained above (including Portland, blended and pozzolanic concretes). The only difference are the impurities contained in the shells but, considering that the raw materials for the production of conventional concrete aren't 100% pure, this shouldn't be a problem.

2. Production

Blue mussel shell (and other bivalve molluscs shell) is composed for calcium carbonate (90%) and silica and phosphates (10%) which can be used as raw materials for several industrial processes like production of quicklime (CaO), paper industry, glass industry, road base stabilization, feed manufacturing fertilizers… But the use we are looking for is the production of cement:

- The first step is to **remove the salt content** of the raw material by washing with fresh water.
- Then they are **calcinated** in an oven at a temperature between 400 and 500 °C, to remove moisture and organic substances.
- Finally, they are **ground** to adjust the particle size of the product.

The result of this process is the production of calcium carbonate of 94% purity (approx.). The following steps for the production of concrete are the same as explained above:

- Production of the cement (with the $CaCO_3$ extracted)
- Mixing of the cement, water and aggregates
- Curing of the concrete

While the shells are being calcinated, gases leaving the oven are at a temperature about 200 °C, contain 4 g/Nm^3 (grams per "Normal" cubic meter) of total organic carbon (approx.) and high moisture content (16% vol.). The organic compounds emitted, are mainly oils and sulfur compounds. This causes a serious problem of odors whose treatment is essential for making the process viable. In addition, these gases contain large amounts of dust.

After the correct treatment (filtering and regenerative thermal oxidation processes) the gases emitted have a content of total organic carbon lower to 10 mg / L and are free of odors.

3. Characteristics

Since there is no evidence of the use of this material before, it is impossible to determine its structural behavior. It will be needed some test of this concrete blend to have a better idea of its characteristics, however, it can be expected a general behavior very similar to the studied concretes.

4. Advantages and disadvantages as reef material

Advantages	Disadvantages
Same as Concrete Advantages and: • Its economic cost is low. Has to be considered the possibility of profit by assuming management of blue mussel waste. • Research and development of new products from recycled materials, allows a wide range of options. • Recycled and marine biological origin materials, such as clusters of bivalve shells are perfectly assimilated by the environment, allowing manage waste effectively.	Same as Concrete Disadvantages and: • In every case in which recycled materials are used, it must be ensured the inertness of the material. • Possible high cost of conditioning and decontamination.

Wood

1. Composition

It is an organic material, a natural composite of cellulose fibers (which are strong in tension) embedded in a matrix of lignin which resists compression. Wood is a heterogeneous, hygroscopic, cellular and anisotropic material. It is composed of cells, and the cell walls are composed of micro-fibrils of cellulose (40% – 50%) and hemicellulose (15% – 25%) impregnated with lignin (15% – 30%).

The chemical composition of wood varies from species to species, but is approximately 50% carbon, 42% oxygen, 6% hydrogen, 1% nitrogen, and 1% other elements (mainly calcium, potassium, sodium, magnesium, iron, and manganese) by weight. Wood also contains sulfur, chlorine, silicon, phosphorus, and other elements in small quantity.

2. Production

Wood to be used for construction work is commonly known as lumber. In Medieval, Europe oak was the wood of choice for all wood construction, including beams, walls, doors, and floors. Today a wider variety of woods is used: solid wood doors are often made from poplar, small-knotted pine, and Douglas fir.

The production of wood for an artificial reef would be simple because of the needing to meet with the London Protocol standards. That's why any treatment for improving wood behavior would not be allowed. So cutting it in the required shape is the only action needed.

3. Characteristics

3.1. Structural behavior

Generally speaking, the center of tree trunk is in compression, and the outer layers are in tension. The stressing is achieved as the inner sapwood shrinks as it dries and becomes heartwood. As the heartwood has lower moisture content it is better able to resist compression.

Since there are many types of wood, physical properties are very different. These are the some examples:

	Greenheart	Balsa	Scots pine
E [GPa]	16	7	14
Strength [MPa]	225	100	40

3.2. Durability and environmental behavior

Untreated wood has a very low durability because it is a highly biodegradable material (less than 10 years for a medium stake). In addition, wet wood properties are quite worse than normal. For the same examples we used before, these are the new results:

	Greenheart	Balsa	Scots pine
Strength [Mpa]	112	47	11

Due to all these things, we are not going to study its environmental behavior.

4. Advantages and disadvantages as reef material

Advantages	Disadvantages
• It is an abundant material. • The complex structure presented by degraded wooden reef can attract large concentrations of fish and is, also, food source. • Wichlund and Shinn (1989) found that marine borers (bivalve molluscs wood borers) by digging tunnels in the wood, increase habitat complexity and provide space for other agencies that will prey fish.	• Wood usually has a short life in seawater and boring organisms and microorganisms break it down quickly. • The deterioration of the reef structure may cause some parts to break and float to areas outside the reef, interfering with other legitimate uses of the sea (sailing, beach use by bathers, etc.). • The processed wood normally used in construction, is often treated to prevent rot, so it may be contaminated with toxic compounds to marine organisms. • Wood is a very light material and must be initially weighed to ensure correct sag and stay in the installation site.

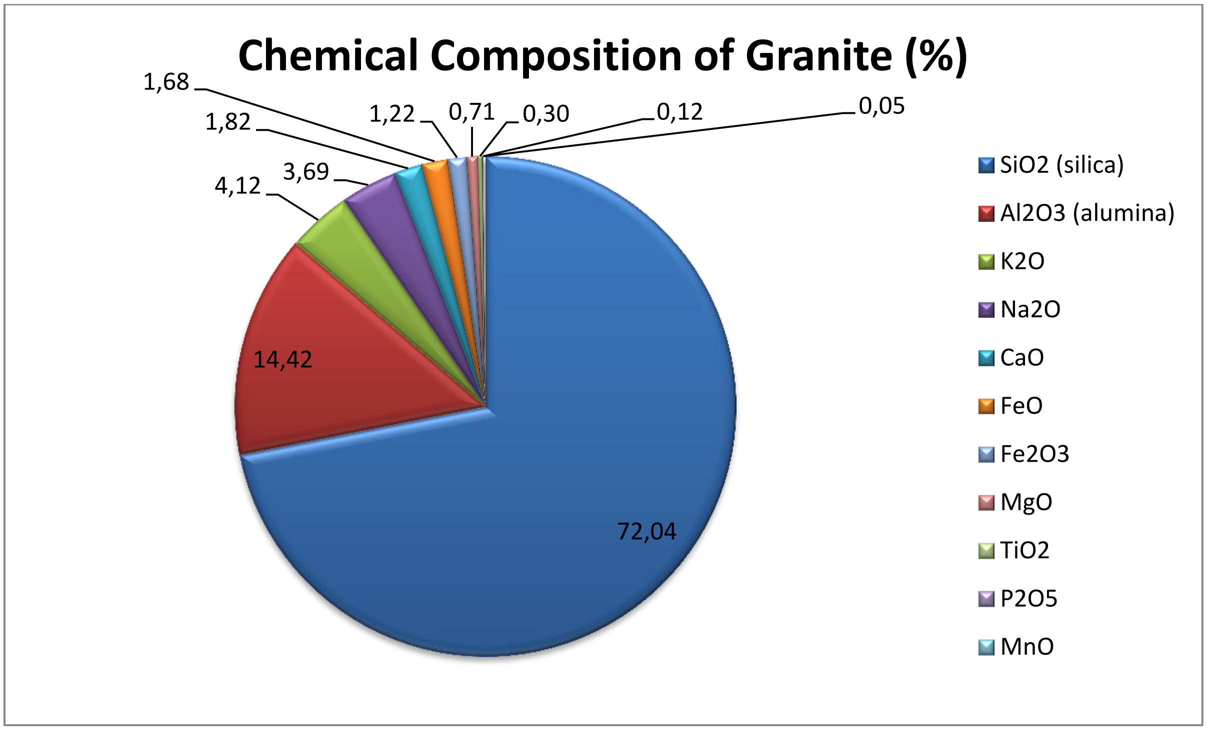
Boulders

1. Composition

In geology, a boulder is a rock with grain size of usually no less than 30 centimeters diameter. In common usage, a boulder is too large for a person to move. Norwegian boulders are mostly granite rocks so this will be the material to be studied.

Granite is a common type of felsic intrusive igneous rock which is granular and phaneritic in texture. These rocks mainly consist of feldspar, quartz, mica, and amphibole minerals. By definition, granite is an igneous rock with at least 20% quartz and up to 65% alkali feldspar by volume.

The chemical composition based on a worldwide average of granite, by weight percent is the following:



2. Production

Two general phases of granite production exist, **quarrying** and **processing**:

- **Quarrying Operations.**

Also known as extraction, consists of removing blocks or pieces of stone from an identified and unearthed geologic deposit. The process is relatively simple: locate or create (minimal) breaks in the stone, remove the stone using heavy machinery, secure the stone on a vehicle for transport, and move the material to storage.

The first step in quarrying is to gain access to the granite deposit. This is achieved by removing the layer of earth, vegetation, and rock unsuitable for product—collectively referred to as overburden—with heavy equipment and transferring to onsite storage for potential use in later reclamation of the site. After the face of the granite is exposed, the stone is removed from the quarry in benches using a variety of techniques suitable to the geology and characteristics of the granite deposit.

Once the bench is cut or split loose from the deposit, heavy equipment is used to lift the granite bench and transfer it to an inspection area for grading, temporary storage, occasional preprocessing into slabs, and eventual shipment from the site. Granite of insufficient quality or size for current demand is stored on-site for future use, crushed for use in paving and construction applications, or stored for site reclamation activities.

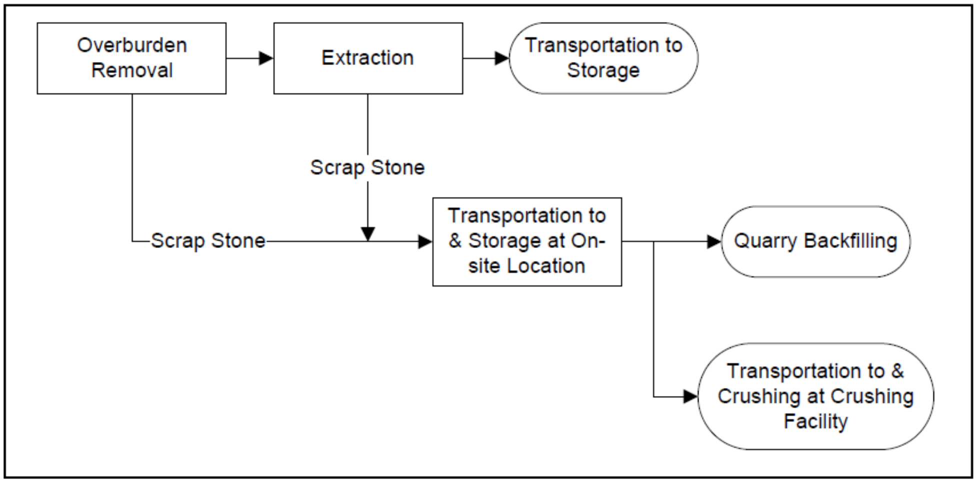


Figure 1. Process flow diagram for granite quarrying operations.

- **Processing.**

The general procedures begin with initial cutting, followed by application of a finish, and conclude with a second cutting or shaping step. The second and third steps may be eliminated, such as when the product is specified to have a "natural" appearance. In the studied case, the product has to be natural, so that processing operations are just transportation to the Limfjorden.

3. Characteristics

3.1. Structural behavior

Granite is the hardest building stone, and granite slabs and granite tiles occupy a prominent place among dimensional stones. The principal characteristics of granite also include high load bearing capacity, crushing strength, abrasive strength, amenability to cutting and shaping without secondary flaws, ability to yield thin and large slabs and, above all, durability.

Density	2.54 - 2.66 g/cc	**Modulus of Rupture**	0.00900 - 0.0379 GPa
Porosity	0.10 - 4.0 %	**Moisture Expansion**	0.0050 %
Permeability	1.0e-9 - 1.0e-6	**Hardness, Shore H**	85 – 100
Abrasive Hardness	37 - 88	**Hardness, Mohs**	5.0 - 7.0
Modulus of Elasticity	20.0 - 60.0 GPa	**Impact Toughness**	2.76 - 11.0 cm/cm²
Tensile Strength, Ultimate	7.00 - 25.0 MPa	**CTE, linear**	3.70 - 11.0 µm/m-°C (20°C)
Compressive Strength	96.5 - 310 MPa	**Specific Heat Capacity**	0.210 - 0.350 J/g-°C
Transverse Strength	9.00 - 38.0 MPa	**Thermal Conductivity**	1.20 - 4.20 W/m-K

3.2. Durability and Environmental Behavior

As noted earlier, granite is one of the longer lasting building stones and is fully compliant with the marine environment, provided that the granite is free of heavy metals, so these features are not an issue at all.

4. Advantages and disadvantages as reef material

Advantages	Disadvantages
• Limestone is comprised of calcium carbonate, the primary component of most natural reefs, which is compatible with the environment. • Quarry rock is a very dense, stable, and durable material, which would be unlikely to move off the reef site except in the most extreme conditions. • From all indications, quarry rock is a good fish attractant and provides a good surface for fouling benthos to attach. • Different size particles of rock can be used to accommodate different life stages of species of interest. • Occasionally, a port dredging is carried on rock bottoms, if this happens, these rocks constitute a suitable source of materials for the construction of artificial reefs.	• Transportation costs to both the staging and reef sites are expensive and will require the use of heavy equipment. • Some rocks may contain high levels of heavy metals that can be released into the sea by leaching. • Quarry rock is usually not a donated material so an initial cost would have to be assumed by the reef builder.

Summary and Viability

Material	Advantages	Disadvantages	Considerations	Viability
Concrete	• Perfectly compatible with the marine environment. • Highly durable, stable and readily available. • Flexible to mold in a wide range of shapes. • Provides a suitable habitat for colonization, growth and shelter of fouling organisms, fish and invertebrates. • Can be produced *in situ*.	• Requires the use of heavy equipment to manipulate it. • Requires the use of heavy marine equipment to place it (costly and dangerous). • Its weight increases the chances to break during the placement. • High carbon footprint during production.	• Use of pozzolanic cement. • Use of recycled artificial pozzolans. • Use of recycled aggregates (controlled). • Low content of tricalcium aluminate. • Additives should be banned. • Strength not below 19.62 MPa. • Dosage not below 350 Kg cement/m^3. • Maximum size of 20 mm for aggregate.	Viable (efficient alternative)
Blue Mussel Concrete	Same as Concrete Advantages and: • Low economic cost (waste management). • Research and development of new products from recycled materials. • Recycled marine biological materials are perfectly assimilated by the environment.	Same as Concrete Disadvantages and: • Must be ensured the inertness of the material. • Possible high cost of conditioning and decontamination.	(Same as Concrete Considerations)	Viable (possibility of develop a new material)
Wood	• Abundant material. • Can attract fish and is food source (even degraded wood). • Marine borers increase habitat complexity and provide space for other agencies that will prey fish.	• Short life in seawater and microorganisms break it down quickly. • Broken parts can float to areas outside the reef. • It can´t be processed wood. • Must be weighed to ensure correct sag and stay.	• Use of big wood structures. • Use of resistant wood. • Use of heavy wood.	No viable
Boulders	• Fully compatible with the environment. • Very dense, stable, and durable material. • Good fish and benthos attractant. • Different rocks can accommodate different life stages. • Dragged rocks constitute a suitable source of materials.	• Transportation costs are expensive. • Requires the use of heavy equipment to manipulate it. • Requires the use of heavy marine equipment to place it (costly and dangerous). • May contain heavy metals. • Quarry rock is not a donated material.	• Need to ensure the absence of heavy metals. • Carbon footprint of extraction and transportation from Norway may be too high.	Viable (current solution)