# SOUTHERN CALIFORNIA EDISON

# EXPERIMENTAL KELP REEF, WEIGHT CALCULATIONS

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# EXECUTIVE SUMMARY

This report discusses a project by Southern California Edison (SCE) to construct an experimental kelp reef from hard substrate materials placed over a natural sandy bottom. The reef is designed to test kelp growth on artificial reefs by varying the percent coverage and types of hard substrate. The two types of hard substrates that will be used to construct the experimental reef are quarry rock and recycled concrete. The rocks will be obtained from a quarry and the concrete will be obtained from demolished structures such as curbs and gutters, bridges, homes, piers, etc. The three hard-substrate coverages by rock and concrete studied are 17%, 34%, and 68% coverage. Two methods of growing kelp on the hard substrate will be investigated. The first method is by allowing the kelp to grow naturally on the hard substrate, and the second method is transplanting the kelp onto the module to enhance initial recruitment of the kelp. The transplanted kelp will be tested on the 34% hard-substrate coverage area. The objective of this report is to estimate the quantity (weight) of rock and concrete necessary to construct the experimental kelp reef.

Each experimental reef module will be 132 by 132 ft, square (40 by 40 m), defined on the sea bottom. The reef design requires the pieces of rock and concrete be placed on the ocean floor as uniformly as possible over each module, preferably not stacked, piled, or clumped together. A set of eight modules consisting of all permutations of material type and coverage is called a Block. There are seven blocks comprising the experiment and they will be placed offshore in about 40-ft water depth near San Clemente, California. The total area of the experimental reef modules is 22.4 acres.

Coastal Environments (CE) compiled measurements of actual substrate pieces (rocks and concrete) which would be available for the project. A relationship was established between length, width, and height of the pieces from the field measurements. The pieces tended to be more slab- or splinter-like than cubes or spheres. Based on the geometric properties measured in the actual rocks and concrete examined, the weight of the material required for the experimental reef was estimated.

Four different calculation methods were examined: (1) an ideal case, (2) a deterministic, (3) a probabilistic, and (4) a worst case. The ideal case method gives the minimum material necessary to achieve the project goals. The deterministic method is based on the mean of the geometric properties of the pieces measured in the field. The area of coverage defined for each module was divided by the coverage area of this average piece to give the number of pieces necessary for each module. The corresponding total weight is the product of the number of pieces times the average weight per piece. The probabilistic method produced random pieces (in terms of length, width, and height), which simulated the observed actual pieces. The surface

areas of the random pieces were added together to achieve the coverage area. Then, the weight of these pieces were added together to give the total weight. The worst case method gives an upper bound on the weight necessary to achieve the project goals. This method assumes substrate pieces which were geometrically undesirable, and poorly deployed.

After the four estimates were completed for both material types (rock and concrete), the results were carefully examined to quantify the total weight of the rock and concrete material required for the project. The total quantity of rocks and concrete based on the above design are: 16,000 tons of rock and 12,000 tons of concrete. These estimates for the rocks and concrete required for the project differ from the previous estimates, given in the Program Environmental Impact Report (PEIR) by Resource Insights (1998). CE's weight estimate was lower for the rock and higher for the concrete. The differences were because of the inaccurate assumptions made in the previous calculations regarding the shape of the rocks and the shape and density of the concrete.

# SAN ONOFRE MARINE MITIGATION PROGRAM: EXPERIMENTAL KELP REEF WEIGHT CALCULATIONS

## 1. INTRODUCTION

This report gives an estimate for the weight of rocks and concrete necessary to construct an experimental kelp reef according to a design proposed by Southern California Edison (SCE). SCE ultimately plans to create a mitigation reef of 150 acres that will be designed to encourage the growth of kelp and its attendant biota. Before construction of the actual mitigation reef, a 22.4-acre experimental reef is planned, where various reef designs will be tested.

The Experimental Reef will be observed over a period of five years to assess which reef designs promote the most successful kelp forests. The experimental reef consists of 56 modules. Each experimental reef module will be 132 by 132 ft, square (40 by 40 m), defined on the sea bottom. Two hard substrate materials are proposed for the experiment: quarry rock and recycled concrete. The ratio of rock or concrete coverage to the remaining exposed natural sand is defined as percentage of cover. For example, 34% hard substrate coverage means the reef design covers 34% of the module area with rock or concrete over the local thin veneer of native sand (~1-ft depth). The reef will be built on the sandy bottom, therefore when 34% of the area is covered by the hard substrate, 66% of the area will be covered by sand. The placement methods need to be selected such that minimal clumping or layering of the experimental substrate occurs.

This report provides a refined estimate of construction material quantities (weight and volume), in comparison to previous estimates for the project. The new estimates are necessary for two reasons. First, the parameters of the experiment have changed since the previous studies were performed. Second, recent field observations of quarry rock and recycled concrete have led to accurate estimates and calculations for rocks and concrete required for the project.

## 2. PREVIOUS STUDIES

This Chapter reviews three previous studies of rock and concrete quantity estimates. The reports include a Preliminary Plan conducted by SCE (1997), Specifications for the San Clemente Artificial Reef, Phase I by Coastal Resources Associates (CRA 1997), and a Draft Program Environmental Impact Report (PEIR) by Resource Insights (1998). The volume calculations from each study are outlined in Table 2-1.

The SCE Preliminary Plan listed some sample construction materials, including quarry rock from two Connoly-Pacific quarries. The plan assumed the coverage-area and volume properties of the quarry rock and concrete pieces as midway (average) between a cube and a sphere using a specific gravity of approximately 2.70 (168 lbs/ft$^3$) for rock and 2.20 (137 lbs/ft$^3$) for concrete. Then, they calculated the corresponding weight. Specific gravity is defined as the density ratio of the material to water. Specific gravity is the ratio of the material density to water density.

CRA (1997) assumed the shape of individual rock pieces was intermediate between a cube and a sphere and the concrete pieces would measure 2 ft x 3 ft x 0.5 ft (with a specific gravity of 2.20). Also, the report estimated that between 10 and 30% overlap would occur because the rock or concrete pieces would pile on top of each other. The CRA report utilized the same assumptions for the quarry rock as the SCE Preliminary Plan and the weight estimates were similar. The CRA (1997) calculated weight for the required concrete for the project is lower than SCE's estimate (1997).

# 3. EXPERIMENTAL REEF DESIGN

The experimental reef consists of 56 modules; 28 modules will use rock as the hard substrate, and 28 modules with concrete. The module locations are shown in Figure 3-1.

The rocks will be obtained from a quarry and the concrete will be obtained from demolished structures such as curbs and gutters, bridges, homes, piers, etc. The three hard-substrate coverages for the project are 17, 34, and 68% surface-area coverage. Two methods of growing kelp on the hard substrate will be investigated. The first method is by allowing the kelp to develop and grow naturally on the hard substrate, and the second method is transplanting the kelp onto the module to enhance initial recruitment of the kelp. Transplanted kelp will only be tested on the 34% coverage area. For each material, there will be four tests: Low coverage (17% substrate); medium coverage (34% substrate); high coverage (67% substrate), and transplanted kelp (34% substrate with transplanted kelp). For purposes of quantity calculation, the transplanted kelp modules are considered identical to medium coverage modules.

A set of eight modules consisting of all permutations of material type and amount is called a Block. There are seven blocks comprising the experiment and will be placed offshore of San Clemente, California, in water depth ranging from 25 to 40 ft. The total area of the experimental reef modules is 22.4 acres. A summary of the experiment modules is given in Table 3-1.

The SCE experimental reef will be constructed as a low-relief reef (preferably, a single layer of rock or concrete, with minimum piling of pieces, and no piece larger than 3.3 ft (1 m) in diameter). The experimental reef modules will be placed on a thin "veneer" of sand (~1 ft) in order to avoid burial of the artificial reef.

**Table 2-1. Previous quantities estimated for SCE's experimental kelp reef, in tons/acre.**

| | *Previous Estimates* | | |
|---|---|---|---|
| | **SCE Jun 97** | **CRA Oct 97** | **PEIR Nov 98** |
| ***Rock*** | | | |
| Low coverage (17%) | 1,421 | 1,487 | 1,450 |
| Medium coverage (34%) | 2,843 | 2,949 | 2,875 |
| High coverage (67%) | 5,685 | 5,821 | 5,675 |
| ***Concrete*** | | | |
| Low coverage (17%) | 1,158 | 282 | 275 |
| Medium coverage (34%) | 2,316 | 615 | 600 |
| High coverage (67%) | 4,632 | 1,333 | 1,300 |

**Table 3-1. Parameters for the experimental reef.**

| Substrate type | Coverage | No. of modules |
|---|---|---|
| Rock | 17% | 7 |
| | 34% | 14[a] |
| | 67% | 7 |
| Concrete | 17% | 7 |
| | 34% | 14[a] |
| | 67% | 7 |
| | **Total number of modules** | **56** |

[a] includes the modules designated for transplanted kelp.

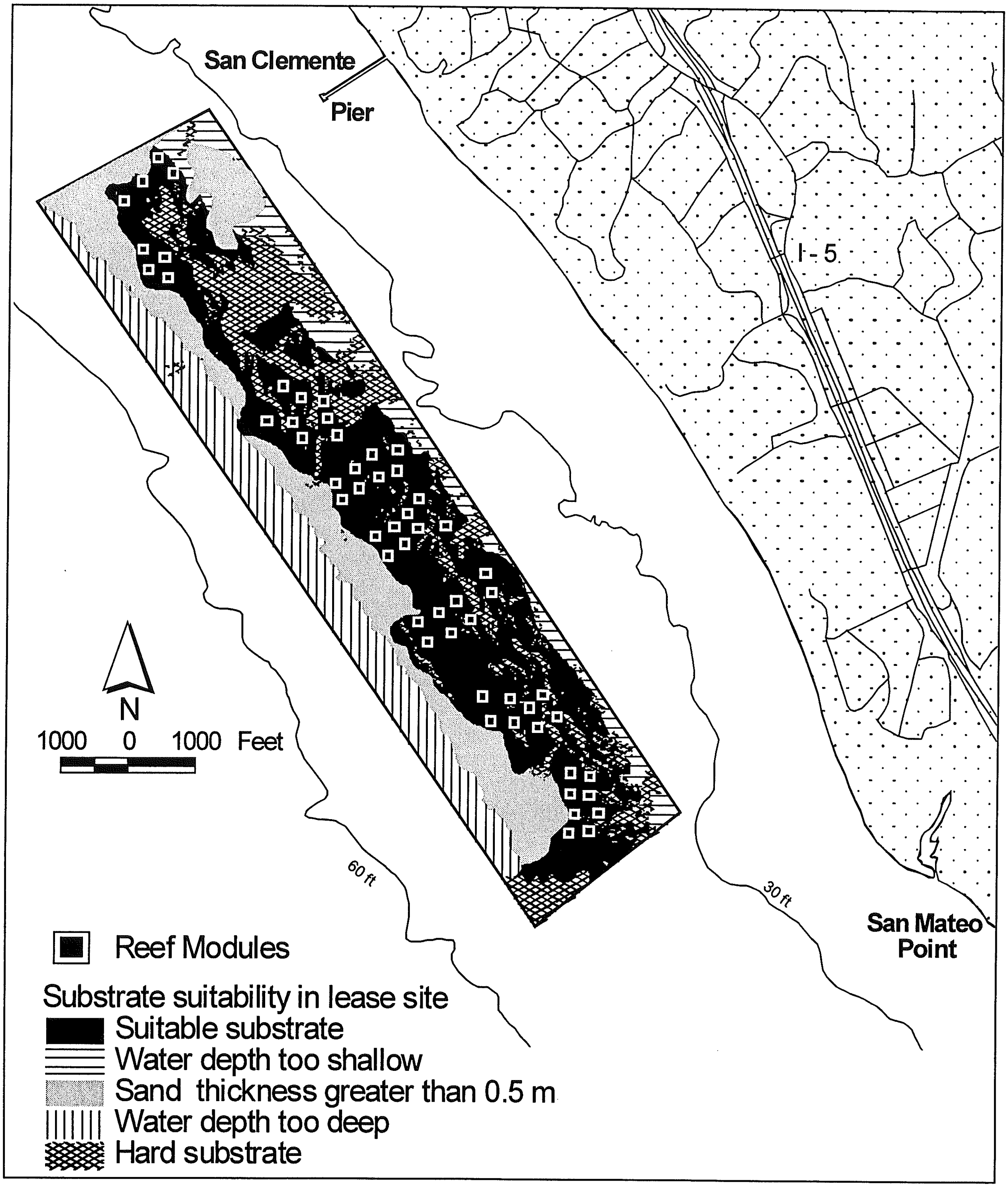



**Figure 3-1. Location map of experimental reef modules at San Clemente, California.**

# 4. FIELD OBSERVATIONS OF AVAILABLE MATERIAL

Field measurements of rock and concrete pieces were made. The pieces were measured along the longest dimension for the length ($l$). Then, the two other orthogonal dimensions, width ($w$) and height ($h$) were measured. The measurements were tabulated and statistical properties (Mean, Standard Deviation) were determined for each dimension separately, and each material separately.

Material observed at quarries tended to be very angular. A minority of the pieces resembled cubes or spheres. Shapes more like "slabs" (height much less than width or length) or "splinters" (height *and* width both much less than length) were common. Figures 4-1 and 4-2 show plots of length versus width and height for both, rocks and concrete. The plots show that the length is greater than the width and much greater than the height, indicating a more slab-like or splinter-like shape, for both rock and concrete rubble. Available stockpiles of rock appeared to be poorly-graded (i.e., well-sorted with little variation in size). Available stockpiles of concrete rubble appeared to be well-graded (i.e., varying greatly in size).

It is important to account for the angular shapes when calculating volumes and quantities. The selection of thinner, more "slab-like" rocks would reduce the total volume required because the slab may safely be assumed to occupy the same bottom-coverage area as the cube, but requires less volume, less mass, and consequently, less construction effort.

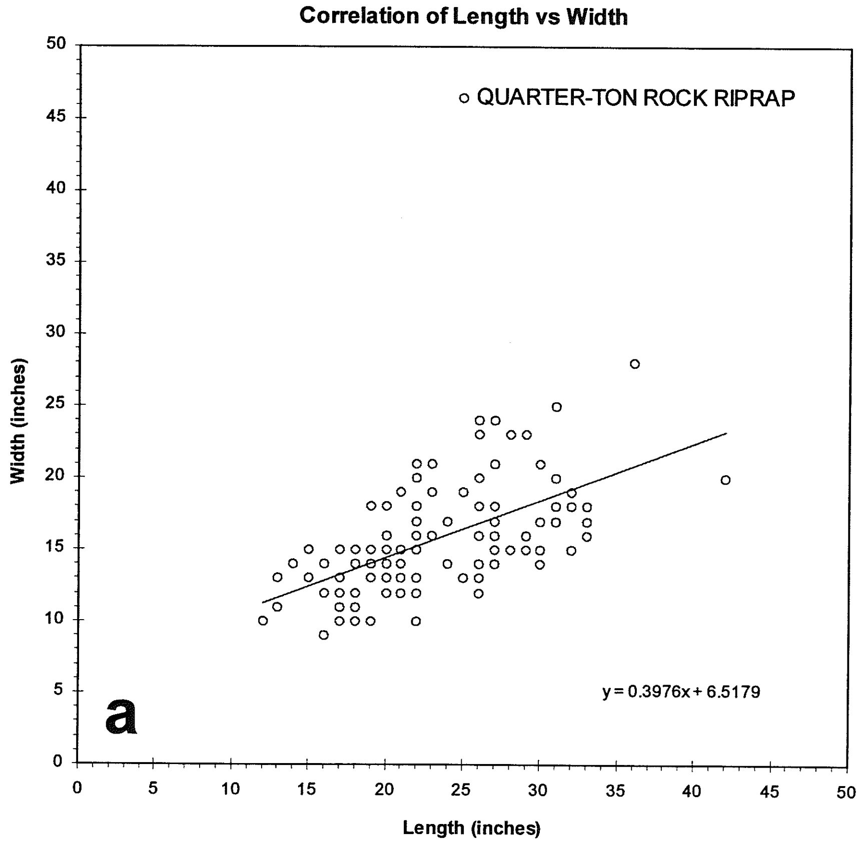
# 5. VOLUME / WEIGHT CALCULATIONS

This Chapter outlines CE's weight estimates. Four calculation methods were performed and compared, and are discussed below.

## 5.1. Ideal Case

The ideal case is formulated to determine the minimum quantity needed for reef construction. The ideal case represents an artificial reef constructed with the least material possible to optimally achieve design goals. This case is not the least-cost option because realistic construction methods contain some uncertainties, which would reduce construction costs.

The ideal case assumes that no clumping or overlapping occurs and that the different experiment coverages are accurately obtained. For an ideal case, the quarry rock would have to be carefully selected to ensure only slab-like pieces are used. The dimensions of an ideal piece of quarry rock would measure around 24 in. x 18 in. x 12 in. Ideal concrete slabs should be 6 in. high to conform to the minimum reef design of 6 in. above the natural sand.



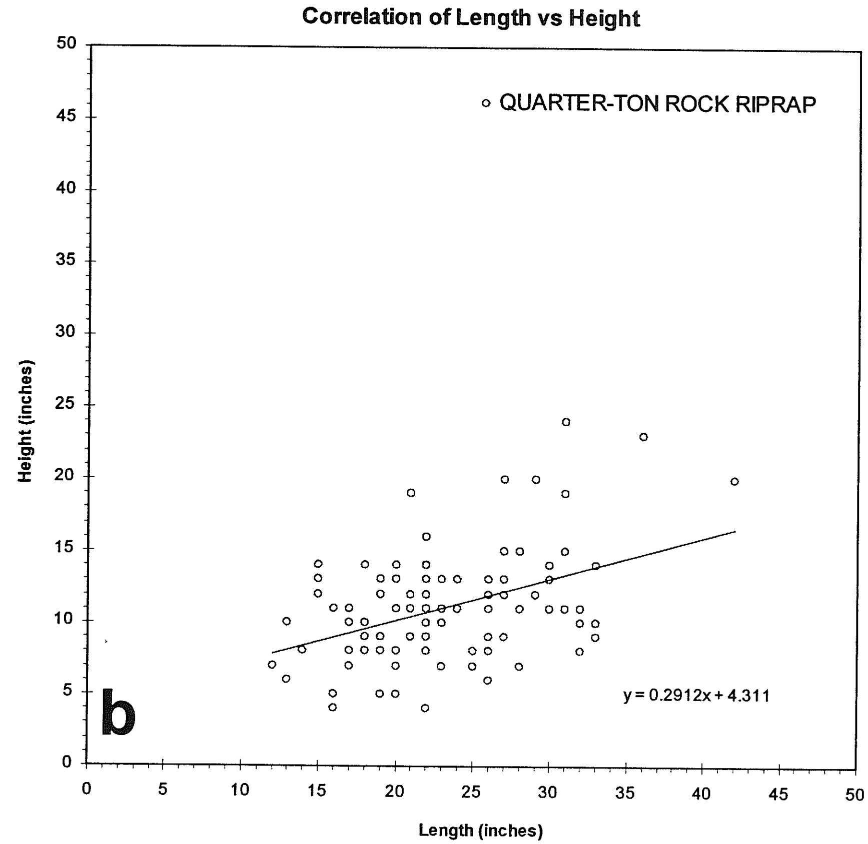




**Figure 4-1. Correlation plots for observed pieces of rock for length versus width (a) and length versus height (b).**

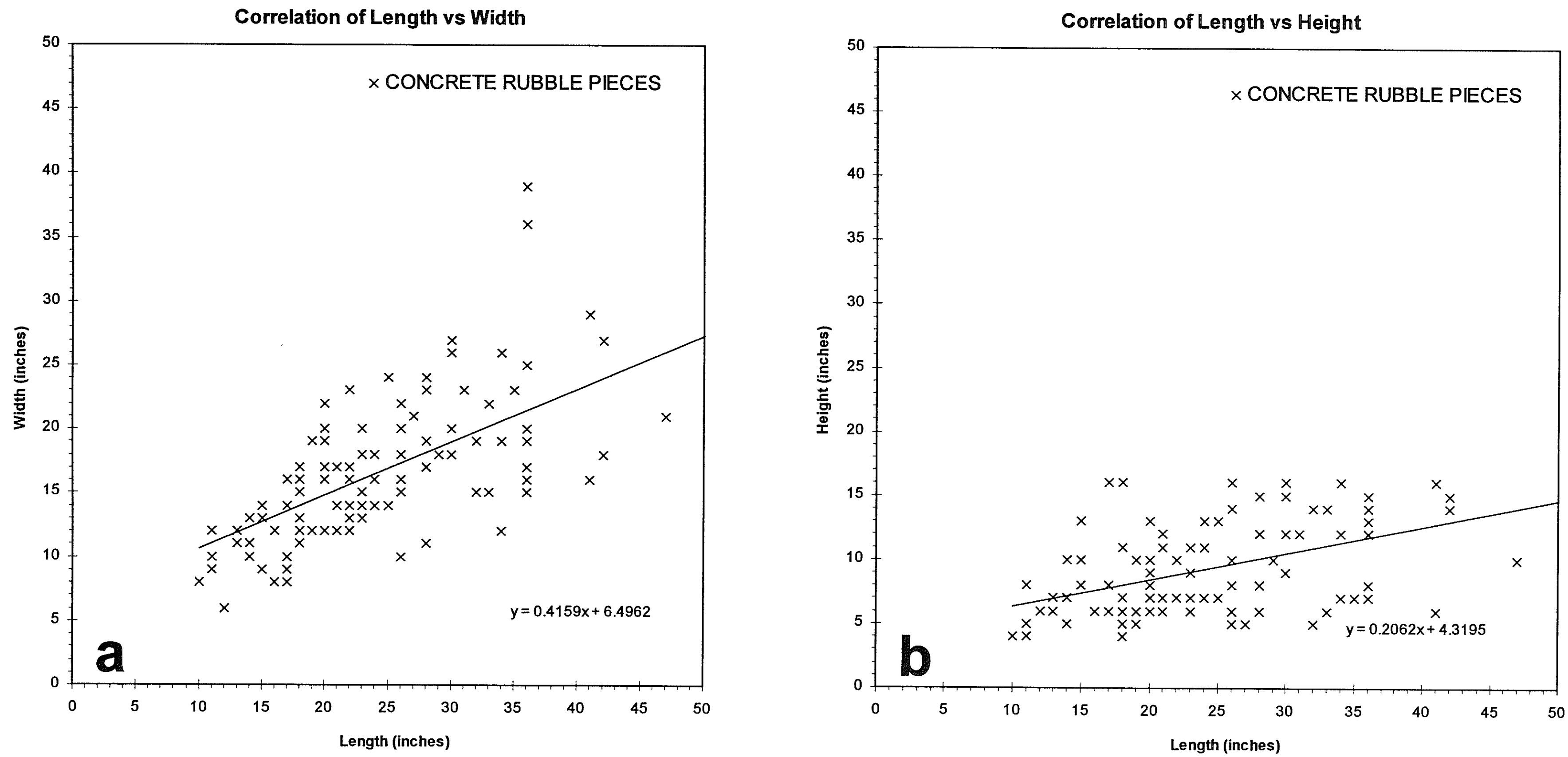



**Figure 4-2. Correlation plots for observed pieces of concrete rubble for length versus width (a) andlength versus height (b).**

For the ideal case, the length and width of the concrete pieces is not needed to calculate volume or weight since all pieces will be uniformly placed on the ocean floor. The calculations to determine the ideal amounts are found in Appendix B and the results are presented in Table 5-1.

## 5.2. Deterministic Method

The deterministic method provides a volume estimate based on mean geometric properties of pieces measured in the field and accounts for the angularity of the observed pieces. The rock and concrete materials can be classified into three shapes: cubes, slabs, and splinters. In order to define the shapes mathematically, the concept of "Angularity" is introduced. Angularity (Krock 1992) is the ratio of the longest dimension, length (squared), to the product of the other two perpendicular dimensions for any specific rock, where $l$ = length, $w$ = width, $h$ = height, and $A$ = angularity, such that $A = l^2 / (w) \times (h)$.

The pieces were classified as cubes, slabs, and splinters based on their angularity and the ratio between the width and height ($w/h$). A piece is defined as a cube when the angularity and the ratio $w/h$ are both less than 2; a splinter when the angularity is above 2, but $w/h$ is less than 2; and a slab when the angularity and $w/h$ are both above 2.

For this method, each shape (cube, slab, or splinter) was assumed to have appropriate volumetric and surface area properties. The shapes were also assumed to be simple rectangular prisms. The average surface area and volume were calculated for each shape independently (cubes, slabs, splinters). Then, the properties for one "average" piece were determined as the weighted-average of the three shapes based on the observed distribution of the shapes within the available stockpile. For example, the rock pile was estimated to contain 15% slabs, 60% splinters, and 25% cubes.

Based on the experiment parameters of 17, 34, and 67% bottom coverage, a total quantity was calculated from the relationship between coverage area and volume. It should be emphasized that this relationship was determined with a limited amount of field observations (approximately 100 pieces for each material, whereas the total project would use tens of thousands of pieces). Calculations to determine the deterministic amounts are found in Appendix C and the results are presented in Table 5-1.

## 5.3. Probabilistic Method

Using the same field measurements as the deterministic method another analysis technique was applied based on the statistical properties of rock and concrete. Separately for each material (rock and concrete), the sample measurements were tabulated and statistical parameters of the pieces (i.e., length, width, and height) were established (mean and standard deviation). Then, a Random Number Generator generated "random" substrate pieces having length, width, and height, conforming to the statistical dimension properties observed in each material (rock or concrete).

The surface area and volume of these random pieces varied between rock and concrete. Concrete pieces were assumed, on average, to be slab-like. Therefore, their properties were based on a simple rectangular prism. For the rocks, however, the pieces were modeled as elliptical cylinders, to reflect the chipping and irregularities observed in the actual samples. Using the dimensions of an elliptical prism, a conservative volume estimate is calculated, providing a safety factor similarly to the rectangle-prism model for the deterministic case.

The surface areas and volumes of the generated random pieces were added together until the bottom coverage was achieved for each module (17, 34, or 67% coverage). Six trials were conducted, each trial with new random pieces, and were averaged to determine the final weights and volumes. Calculations for the probabilistic amounts are found in Appendix D and the results are presented in Table 5-1.

## 5.4. Worst Case

To establish an upper bound for material quantities, a worst case was considered. For this case, the rocks would have an angularity about 20-30% worse than the measured rocks (more rounded and less slab-like) and the concrete would have a height of 15 in. This method assumes that geometrically undesirable materials are used. Undesirable rocks would be large and relatively rounded and provide little bottom-area coverage for their given weight. The undesirable concrete slabs would be thicker than the 6-in. minimum acceptable reef height.

An average-size undesirable piece for each material (rock and concrete) was considered. The computed weight of the average-size pieces was increased by 10% to allow for possible overlapping and stacked pieces. The results obtained give an upper bound of material quantity for the project. Calculations to determine the worst case amounts are found in Appendix E and the results are presented in Table 5-1.

## 5.5. Total Weight for Rock and Concrete

Table 5-1 gives the actual volume estimates for the four methods described above. The total quantity was then selected with some allowances for the uncertainties inherited in the calculations. The final estimate recommends 16,000 tons of rock and 12,000 tons of concrete. Table 5-2 compares our estimate with the previous estimate calculated by the PEIR.

**Table 5-1. Weight estimates for four methods.**

| Case | Material | Coverage | Tons per Acre | Tons per Module | No. of Pieces per Module | Total Tonnage per Coverage | TOTAL TONNAGE |
|---|---|---|---|---|---|---|---|
| Ideal | *Rock* | Low | 629 | 245 | 2,891 | 1,717 | **15,356** |
| | | Medium | 1,257 | 491 | 5,781 | 6,870 | |
| | | High | 2,477 | 967 | 11,393 | 6,769 | |
| | *Concrete* | Low | 278 | 108 | custom [a] | 759 | **6,785** [a] |
| | | Medium | 555 | 217 | custom | 3,035 | |
| | | High | 1,094 | 427 | custom | 2,991 | |
| Deterministic | *Rock* | Low | 642 | 250 | 1,256 | 1,753 | **15,678** |
| | | Medium | 1,283 | 501 | 2,513 | 7,014 | |
| | | High | 2,529 | 987 | 4,951 | 6,911 | |
| | *Concrete* | Low | 491 | 192 | 1,169 | 1,341 | **11,994** [b] |
| | | Medium | 982 | 383 | 2,339 | 5,366 | |
| | | High | 1,935 | 755 | 4,609 | 5,287 | |
| Probabilistic | *Rock* | Low | 654 | 255 | 1,292 | 1,788 | **15,983** |
| | | Medium | 1,308 | 511 | 2,584 | 7,150 | |
| | | High | 2,578 | 1,006 | 5,092 | 7,045 | |
| | *Concrete* | Low | 399 | 192 | 850 | 1,089 | **9,741** [c] |
| | | Medium | 797 | 383 | 1,700 | 4,358 | |
| | | High | 1,935 | 755 | 3,350 | 4,294 | |
| Worst | *Rock* | Low | 903 | 353 | 1,411 | 2,469 | **22,074** |
| | | Medium | 1,807 | 705 | 2,822 | 9,875 | |
| | | High | 3,561 | 1,390 | 5,561 | 9,730 | |
| | *Concrete* | Low | 833 | 325 | custom [d] | 2,276 | **20,354** [d] |
| | | Medium | 1,666 | 650 | custom | 9,106 | |
| | | High | 3,283 | 1,282 | custom | 8,972 | |

a) Concrete pieces were assumed to be 6" slabs. Number of individual pieces was not determined.
b) Assumed a mixture of concrete slabs vs. other shapes (cubes, splinters) based on observation.
c) Assumed concrete slabs vary from 6" to 12" in height.
d) Assumed concrete pieces were nearly cubical in shape. Number of individual pieces was not determined.

**Table 5-2. Comparison between various estimates and made for the experimental kelp reef, tons per acre.**

| | *Previous Estimate* | *New Estimate* |
|---|---|---|
| | **PEIR Nov 98** | **Coastal Environments Feb 99** |
| ***Rock*** | | |
| Low density (17%) | 1,450 | 700 |
| Medium density (34%) | 2,875 | 1,400 |
| High density (68%) | 5,675 | 2,800 |
| ***Concrete*** | | |
| Low density (17%) | 275 | 500 |
| Medium density (34%) | 600 | 1,000 |
| High density (68%) | 1,300 | 2,000 |

### 5.6. Possible Errors in Weight Estimate

The actual quantities of both types of substrate necessary to achieve the project goals may vary from this study's estimate for several reasons, including: 1) the supply of rock or concrete may not conform to the statistical parameters of the observed sample (less slab-like and more rounded or cubical), 2) the pieces are not scattered uniformly, but rather in piles or multiple layers, or 3) the random nature of the pieces may produce an uncertainty.

Among the six trials conducted for each material in the Probabilistic Method, there was an uncertainty (standard deviation) of 2.3% by weight for the rock, and 7.4% by weight for the concrete. Based on the simulated study Table 5-3 gives the project lower and upper estimates for the rock and concrete weight required for the project.

## 6. CONCLUSIONS

Weight estimates of rock and concrete pieces required for the experimental reef are given in Table 6-1. Four different methods of estimation were compared to reduce the uncertainty associated with the estimate. Average dimensions of rocks are 2 ft (length) by 1.5 ft (width), by 1 ft (height), and 2.5 ft (length) by 1.5 ft (width), by 8 in. (height) for concrete. It is reasonable to assume a total error of about 5 to 10% of the final Recommended Project Estimate. As indicated in Table 5-3, based on this study, upper estimates for the amount of rock and concrete required for SCE's experimental reef are 16,800 tons and 13,200 tons, respectively.

**Table 5-3. Project weight estimates with lower and upper boundaries, tons**

| Weight | Rock (tons) | Concrete (tons) |
|---|---|---|
| Total project | 16,000 | 12,000 |
| Lower limit | 15,200 [a] | 10,800 [c] |
| Upper limit | 16,800 [b] | 13,200 [d] |

a. 5% less than the project rock weight
b. 5% greater than the project rock weight
c. 10% less than the project concrete weight
d. 10% greater than the project concrete weight

**Table 6-1. Weight Estimates for SCE's Experimental Kelp Reef Design (56 modules)**

| | *Estimate* |
|---|---|
| ***Rock*** | |
| Low density (17%) | 250 tons/module |
| Medium density (34%) | 500 tons/module |
| High density (68%) | 1,000 tons/module |
| **Experiment Total** | **16,000 tons** |
| ***Concrete*** | |
| Low density (17%) | 190 tons/module |
| Medium density (34%) | 380 tons/module |
| High density (68%) | 760 tons/module |
| **Experiment Total** | **12,000 tons** |

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# APPENDIX A.
# EXPERIMENT PARAMETERS AND RESULTS SUMMARY

## A.1. Experiment Parameters

**Table A-1. New Experimental Reef Parameters.**

| Substrate type | Coverage | No. of modules |
|---|---|---|
| Rock | 17% | 7 |
| Rock | 34% | 14 |
| Rock | 67% | 7 |
| Concrete | 17% | 7 |
| Concrete | 34% | 14 |
| Concrete | 67% | 7 |
| | **Total number of modules** | **56** |

One module = 40 x 40 m = 0.39 acres = 17,004 $ft^2$

Low coverage, 1 module = 17% coverage = 0.066 acre (2,891 $ft^2$)

Medium coverage, 1 module = 34% coverage = 0.133 acre (5,781 $ft^2$)

High coverage, 1 module = 67% coverage = 0.261 acre (11,393 $ft^2$)

## A.2. Design Parameters

Minimum design reef height = 6 in.

Concrete density = 150.00 lbs/$ft^3$ (2,400 kg/$m^3$) Specific Gravity = 2.40

Rock density = 169.75 lbs/$ft^3$ (2,700 kg/$m^3$) Specific Gravity = 2.72

(The rock density and Specific Gravity are consistent with the Otay quarry values.)

## A.3. Experiment Results and Estimates

***Recommended Project Estimates***

**Quarry Rock = 16,000 tons**[a]
**Recycled Concrete = 12,000 tons**[a]

[a] numbers are rounded up to nearest 1,000 tons

# APPENDIX B.
# IDEAL WEIGHTS OF EXPERIMENTAL SUBSTRATE

The ideal case method gives the minimum material condition for the experiment. This is achieved by using flat, slab-like stones, and 6-in. high concrete slabs of material. First, we estimate an "average" piece, then surface area, volume, and weight of the average piece are calculated.

The number of pieces needed to achieve the desired coverage density is calculated by dividing the square footage of bottom coverage desired by the plan-view surface area, then multiply the number of pieces by an average weight to find total tonnage required. The calculations are presented below and in Table B-1. For the ideal case, 15,356 tons of rock and 6,785 tons of concrete would be needed for the Experimental Reef.

## Calculations for Quarry Rock

- Assume ideal rock slabs have the following averaged dimensions:

| | | |
|---|---|---|
| Length (l) | = | 24 in. |
| Width ($w$) | = | 18 in. |
| Height ($h$) | = | 12 in. |

- For comparison to actual available materials

| | | |
|---|---|---|
| Angularity | = | 2.67 |
| Ratio ($w/h$) | = | 1.50 |

- Then, an average ideal piece has:

| | | |
|---|---|---|
| Area | = | 3.00 $ft^2$ |
| Volume | = | 3.00 $ft^3$ |
| Weight | = | 509.25 lbs |

- To achieve different coverages per module:

| | | | | | | |
|---|---|---|---|---|---|---|
| Low coverage | = | 964 pieces | = | 490,698 lbs | = | 245 tons |
| Medium coverage | = | 1,927 pieces | = | 981,395 lbs | = | 491 tons |
| High coverage | = | 3,798 pieces | = | 1,933,926 lbs | = | 967 tons |

**Table B-1. Total tonnage of quarry rocks for the ideal case.**

| Coverage | No. Modules | Tons/Acre | Total Tonnage |
|---|---|---|---|
| Low (17%) | 7 | 629 | 1,717 |
| Medium (34%) | 14 | 1,257 | 6,870 |
| High (67%) | 7 | 2,477 | 6,769 |
| **Total for Experimental Reef** | **28** | **n/a** | **15,356** |

## Calculations for Concrete

- Assume ideal concrete slabs have the following averaged, dimensions:

| | | |
|---|---|---|
| Length (l) | = | 12 in. |
| Width ($w$) | = | 12 in. |
| Height ($h$) | = | 6 in. |

- Then, an average ideal piece has:

| | | |
|---|---|---|
| Area | = | 1.00 $ft^2$ |
| Volume | = | 0.5 $ft^3$ |
| Weight | = | 75.0 lbs |

- To achieve different coverages per module:

| | | | | | | |
|---|---|---|---|---|---|---|
| Low Coverage | = | 2,891 pieces | = | 216,803 lbs | = | 108 tons |
| Medium Coverage | = | 5,781 pieces | = | 433,606 lbs | = | 217 tons |
| High Coverage | = | 11,393 pieces | = | 854,459 lbs | = | 427 tons |

**Table B-2. Total tonnage of concrete slabs for the ideal case.**

| Coverage | No. Modules | Tons/Acre | Total Tonnage |
|---|---|---|---|
| Low (17%) | 7 | 278 | 759 |
| Medium (34%) | 14 | 555 | 3,035 |
| High (67%) | 7 | 1,094 | 2,991 |
| **Total for Experimental Reef** | **28** | **n/a** | **6,785** |

# APPENDIX C.
# DETERMINISTIC WEIGHTS OF EXPERIMENTAL SUBSTRATE

Based on measurements taken of hard substrate material, an average piece of each material, rock and concrete, were determined. The method is described below.

The sample pile's content was classified into "Cubes," "Slabs," and "Splinters" based on Angularity and ratio between dimensions. The different shapes have different geometrical properties. To classify each shape, a cube is defined as the angularity and the ratio (*w/h*) are both less than 2; a splinter is a piece where angularity is above 2, but (*w/h*) is less than 2; and a slab is a piece where the angularity and (*w/h*) are all above 2.

A weighted average on the pile was calculated to find an average piece of material. Given the area of the average piece, the number of pieces was calculated to achieve the desired coverage (17, 34, or 67%). A factor of safety was added by the assumption that it was possible for each piece to land sideways, effectively having *l* and *h* (length and width) horizontal, instead of *l* and *w* horizontal. To compensate for this, the simple rectangular prism's plan-view surface area was calculated with an "effective width," which fell in-between *w* and *h*, 75% closer to *w*.

The concrete pile consisted of 75% slab and splinters pieces, not differentiating, because the splinters tended to be big and thick, and 25% cubes. The rock pile consists of 15% slabs, 60% splinters, and 25% cubes.

Tables C-1 and C-4 contain a listing of the field measurements (Data), along with the angularity, ratio of *w/h*, and classification on each piece measured for rocks and concrete, respectively. Tables C-2 and C-5 provide calculations of the weighted average piece for each material and Tables C-3 and C-6 show the final weight calculations for the deterministic method.

The project would require 15,678 tons of rock and 11,994 tons of concrete rubble for construction of the Experimental Reef or 78,740 pieces of rock and 73,230 pieces of concrete rubble.

**Table C-1. Measurements of rock samples obtained from the Nelson&Sloan (Otay) quarry.**

| Sample No. | Length (*l*) | Width (*w*) | Height (*h*) | Angularity | (*w/h*) | Classification |
|---|---|---|---|---|---|---|
| 1 | 15 | 13 | 13 | 1.33 | 1.00 | Cube |
| 2 | 27 | 24 | 20 | 1.52 | 1.20 | Cube |
| 3 | 22 | 20 | 14 | 1.73 | 1.43 | Cube |
| 4 | 20 | 16 | 14 | 1.79 | 1.14 | Cube |
| 5 | 22 | 21 | 12 | 1.92 | 1.75 | Cube |
| 6 | 16 | 12 | 11 | 1.94 | 1.09 | Cube |
| 7 | 23 | 21 | 11 | 2.29 | 1.91 | Splinter |
| 8 | 23 | 16 | 13 | 2.54 | 1.23 | Splinter |
| 9 | 21 | 13 | 12 | 2.83 | 1.08 | Splinter |
| 10 | 17 | 12 | 8 | 3.01 | 1.50 | Splinter |
| 11 | 27 | 17 | 12 | 3.57 | 1.42 | Splinter |
| 12 | 22 | 16 | 8 | 3.78 | 2.00 | Slab |
| 13 | 30 | 17 | 13 | 4.07 | 1.31 | Splinter |
| 14 | 27 | 18 | 9 | 4.50 | 2.00 | Slab |
| 15 | 28 | 23 | 7 | 4.87 | 3.29 | Slab |
| 16 | 14 | 14 | 8 | 1.75 | 1.75 | Cube |
| 17 | 13 | 11 | 6 | 2.56 | 1.83 | Splinter |
| 18 | 36 | 28 | 23 | 2.01 | 1.22 | Splinter |
| 19 | 42 | 20 | 20 | 4.41 | 1.00 | Splinter |

**Table C-2. Dimensions, surface area, volume, and weight of an average pieces of rock.**

| Shape | Length (in.) | Width (in.) | Height (in.) | Effective Width (in.) | Effective Volume ($ft^3$) | Surface Area ($ft^3$) | Weight (lbs) |
|---|---|---|---|---|---|---|---|
| Cube | 19.43 | 17.14 | 13.14 | 13.18 | 1.95 | 1.78 | 330.70 |
| Slab | 25.67 | 19.00 | 8.00 | 14.57 | 1.73 | 2.60 | 293.92 |
| Splinter | 25.78 | 17.22 | 13.11 | 13.66 | 2.67 | 2.44 | 453.38 |

Notes:
1. The pile composition was 25% cubes, 60% splinters, and 15% slabs.
2. The average angularity = 2.83 and the average (*w/h*) = 1.15
3. The average weight per piece = 398.79 lbs/$ft^3$
4. The average plane area per piece = 2.30 $ft^2$
5. Rock specific gravity = 2.72; density = 169.75 lbs/$ft^3$.
6. Effective width is the width of the piece that landed on its height and length instead of its width and length.
7. Effective surface area and volume are calculated from the effective width.

**Table C-3. Weight calculations for rock.**

| Coverage | Per Module | | No. of Modules | Weight per Acre (tons/acre) | Total Weight (tons) |
|---|---|---|---|---|---|
| | No. of Ave. Pieces | Weight (tons) | | | |
| Low (17%) | 1,256 | 250 | 7 | 642 | 1,753 |
| Medium (34%) | 2,513 | 501 | 14 | 1,283 | 7,014 |
| High (67%) | 4,951 | 987 | 7 | 2,529 | 6,911 |
| **Total** | **8,720** | **n/a** | **28** | **n/a** | **15,678** |

**Table C-4. Measurements of concrete rubble from the Nelson & Sloan (Otay) quarry.**

| Sample No. | Length (*l*) | Width (*w*) | Height (*h*) | Angularity | (*w/h*) | Classification |
|---|---|---|---|---|---|---|
| 1 | 18 | 15 | 7 | 3.09 | 2.14 | Slab |
| 2 | 41 | 16 | 16 | 6.57 | 1.00 | Splinter |
| 3 | 26 | 18 | 10 | 3.76 | 1.80 | Splinter |
| 4 | 18 | 16 | 16 | 1.27 | 1.00 | Cube |
| 5 | 15 | 13 | 10 | 1.73 | 1.30 | Cube |
| 6 | 28 | 24 | 12 | 2.72 | 2.00 | Slab |
| 7 | 20 | 20 | 7 | 2.86 | 2.86 | Slab |
| 8 | 18 | 16 | 7 | 2.89 | 2.29 | Slab |
| 9 | 30 | 20 | 15 | 3.00 | 1.33 | Splinter |
| 10 | 23 | 14 | 11 | 3.44 | 1.27 | Slab |
| 11 | 23 | 15 | 9 | 3.92 | 1.67 | Slab |
| 12 | 22 | 13 | 7 | 5.32 | 1.86 | Slab |
| 13 | 42 | 18 | 14 | 7.00 | 1.29 | Splinter |
| 14 | 51 | 21 | 17 | 7.29 | 1.24 | Splinter |
| 15 | 35 | 23 | 7 | 7.61 | 3.29 | Slab |

**Table C-5. Dimensions, surface area, volume, and weight of an average pieces of concrete.**

| Shape | Length (in.) | Width (in.) | Height (in.) | Effective Width (in.) | Effective Volume ($ft^3$) | Surface Area ($ft^3$) | Weight (lbs) |
|---|---|---|---|---|---|---|---|
| Cube | 16.50 | 14.50 | 13.00 | 11.21 | 1.39 | 1.28 | 208.77 |
| Slab or Splinter | 28.00 | 18.08 | 10.25 | 14.75 | 2.45 | 2.87 | 367.44 |

Notes:
1. The pile composition was 25% cubes and 75% slabs and splinters.
2. The average angularity = 3.53 and the average (*w/h*) = 1.29
3. The average weight per piece = 327.77 lbs/$ft^3$
4. The average plane area per piece = 2.47 $ft^2$
5. Concrete specific gravity =2.4; density = 150.0 lbs/$ft^3$.
6. Effective width is the width of the piece that landed on its height and length instead of its width and length.
7. Effective surface area and volume are calculated from the effective width.

**Table C-6. Weight calculations for concrete rubble.**

| Coverage | Per Module | | No. of Modules | Weight per Acre (tons/acre) | Total Weight (tons) |
|---|---|---|---|---|---|
| | No. of Ave. Pieces | Weight (tons) | | | |
| Low (17%) | 1,169 | 192 | 7 | 491 | 1,341 |
| Medium (34%) | 2,339 | 383 | 14 | 982 | 5,366 |
| High (67%) | 4,609 | 755 | 7 | 1,935 | 5,287 |
| **Total** | **8,117** | **n/a** | **28** | **n/a** | **11,994** |

# APPENDIX D.
# PROBABILISTIC WEIGHTS OF EXPERIMENTAL SUBSTRATE

Measurements of hard substrate material (rock and concrete) were analyzed to determine the statistical properties (mean and standard deviation) of each dimension for each material, separately.

A Random Number Generator from Microsoft Excel was used to generate sets of random numbers that conformed to the statistical properties for each dimension. The random number generator asks for the desired type of random number distribution (normal, in this case). It then asks for the mean and standard deviation to calculate the distribution. Essentially, it generates random dimension measurements that have the same properties as the data sample – for example, if the mean length of the data sample is 27.33, as in our case, the mean of all the random Lengths generated would be 27.33.

When this method was first applied, the statistical parameters used to generate the Normal distribution were found inappropriate. For example, random lengths produced had several very small lengths (e.g., 0.33 in.), including some negative ones (as low as –7.0). Besides not making intuitive sense, this violated our assumptions that the longest dimensions of the piece would fall flat on the sea bottom. Therefore, the standard deviation of the sample was adjusted to better represent the intelligent sorting action of the quarry foreman; if the foreman noticed a piece where one dimension was only 0.33 in., for example, he would not put it in the 500-lb rock pile. The adjusted standard deviation was defined for each dimension as (maximum dimension value – minimum dimension value) / 6. This produced a set of random measurements, which was visually checked and deemed reasonable.

The height dimension of the concrete pieces was also adjusted. The preferable sources of concrete rubble were felt to contain mainly slabs, with dimensions evenly distributed from 6 in. to 12 in. high. Therefore, the mean of the concrete rubble height was assigned as 9 in., and a standard deviation of 1 in.

Geometric properties of each piece varied with the material. The randomly generated concrete pieces were assumed to be slabs, so their bottom coverage surface area and their volume were assumed to conform to simple rectangular prisms. The rock pieces, however, were modeled as elliptical cylinders, to reflect the chipping and irregularities observed in the actual samples. (Unlike the deterministic method, the probabilistic method is meant to generate individual rocks, not averages. Using an elliptical prism was a conservative method, because the actual pieces were rarely 90-degree rectangular prisms. The random and realistic nature of this model was believed to provide the same kind of safety factor that the rectangular prism model did for the deterministic case.)

These randomly generated rock and concrete pieces were added and cumulative totals of piece volume and surface area were obtained. In other words, the total surface area climbed as the list went on, and when the total hit 170 square feet or more, that row was selected as covering 1% of one experimental module. (The experimental modules, as defined, are 132 ft by 132 ft, or 17,424 $ft^2$.) For each material, trials were run to find out how many pieces (and what total volume of material) were required to achieve 1% coverage of 1 module. When 174 $ft^2$ (representing 1%) was achieved, the list of randomly generated substrate pieces was called a trial. For each material, six trials were run and the average of the trials taken. Then, that 1% total of material was multiplied by the appropriate factor in order to estimate the material required for each type of coverage – low (17%), medium (34%), and high (67%).

Table C-1 in Appendix C lists the field measurements (data) of quarry rock and concrete slabs. Calculations of the probabilistic trials for each material follow on the next page. From calculating weight with this method, the project would require 15,983 tons of rock and 9,741 tons of concrete rubble for construction of the experimental reef; this represents 80,870 pieces of rock and 53,200 pieces of concrete rubble.

**Table D-1. Statistical properties of the concrete and rock dimension data collected at the Nelson-Sloan Quarry.**

| | Length (in.) | Width (in.) | Height (in.) | W/h |
|---|---|---|---|---|
| *Concrete Slabs* | | | | |
| **Mean** | 27.33 | 17.47 | 9.00** | 1.75 |
| **Std Deviation*** | 6.00 | 1.83 | 1.00** | 0.67 |
| **Min** | 15.00 | 13.00 | 7.00 | 1.00 |
| **Max** | 51.00 | 24.00 | 17.00 | 3.29 |
| *Rock* | | | | |
| **Mean** | 23.42 | 17.47 | 12.32 | 1.53 |
| **Std Deviation*** | 4.83 | 2.83 | 2.83 | 0.54 |
| **Min** | 13.00 | 11.00 | 6.00 | 1.00 |
| **Max** | 42.00 | 28.00 | 23.00 | 3.29 |

* When length and width were given a simple normal probability distribution, small and even negative measurements were occasionally generated. To eliminate this problem we will assume that the concrete rubble is not truly random, but are sorted intelligently. This will be reflected by assigning a standard deviation rather than using the technical definition. The mean will remain the same. Our new standard deviation = (Max-Min)/6.

** Assumed height of desired concrete slabs from 6 in. to 12 in. thick with a mean of 9 in. and a standard deviation of 1.0. This reflects the acquisition of a more desirable source of concrete rubble with less variation than that available at the Nelson-Sloan quarry.

**Table D-2. Example of a probabalistic trial for concrete slabs.**

| Piece No. | Length (in.) | Width (in.) | Height (in.) | Volume ($ft^3$) | Cumulative Volume ($ft^3$) | Area ($ft^2$) | Cumulative Area ($ft^2$) |
|---|---|---|---|---|---|---|---|
| 1 | 12.06 | 12.82 | 6.35 | 0.57 | 0.57 | 1.07 | 1.07 |
| 2 | 24.86 | 18.27 | 9.67 | 2.54 | 3.11 | 3.15 | 4.23 |
| 3 | 19.30 | 18.10 | 8.89 | 1.80 | 4.91 | 2.43 | 6.65 |
| 4 | 29.67 | 16.94 | 8.67 | 2.52 | 7.43 | 3.49 | 10.14 |
| 5 | 32.50 | 15.32 | 8.74 | 2.52 | 9.95 | 3.46 | 13.60 |
| 6 | 27.52 | 18.09 | 9.98 | 2.87 | 12.82 | 3.46 | 17.06 |
| 7 | 24.85 | 17.17 | 6.67 | 1.65 | 14.47 | 2.96 | 20.02 |
| 8 | 20.95 | 14.54 | 8.73 | 1.54 | 16.01 | 2.12 | 22.14 |
| 9 | 40.57 | 17.43 | 10.49 | 4.29 | 20.30 | 4.91 | 27.05 |
| 10 | 33.99 | 18.32 | 8.98 | 3.24 | 23.54 | 4.32 | 31.37 |
| 11 | 40.28 | 21.23 | 7.33 | 3.63 | 27.17 | 5.94 | 37.31 |
| 12 | 35.58 | 20.00 | 10.26 | 4.23 | 31.39 | 4.94 | 42.25 |
| 13 | 19.16 | 18.78 | 9.33 | 1.94 | 33.33 | 2.50 | 44.75 |
| 14 | 30.86 | 16.10 | 9.39 | 2.70 | 36.03 | 3.45 | 48.20 |
| 15 | 31.35 | 17.13 | 8.38 | 2.60 | 38.64 | 3.73 | 51.93 |
| 16 | 23.05 | 18.80 | 9.96 | 2.50 | 41.13 | 3.01 | 54.94 |
| 17 | 26.80 | 16.42 | 6.55 | 1.67 | 42.80 | 3.06 | 58.00 |
| 18 | 39.75 | 17.67 | 7.77 | 3.16 | 45.96 | 4.88 | 62.87 |
| 19 | 27.24 | 17.70 | 9.56 | 2.67 | 48.63 | 3.35 | 66.22 |
| 20 | 24.50 | 14.18 | 8.38 | 1.69 | 50.31 | 2.41 | 68.63 |
| 21 | 29.17 | 20.87 | 9.65 | 3.40 | 53.71 | 4.23 | 72.86 |
| 22 | 23.98 | 18.77 | 9.45 | 2.46 | 56.17 | 3.12 | 75.99 |
| 23 | 25.25 | 19.16 | 10.64 | 2.98 | 59.15 | 3.36 | 79.35 |
| 24 | 43.04 | 15.99 | 11.99 | 4.77 | 63.93 | 4.78 | 84.13 |
| 25 | 30.94 | 15.74 | 8.97 | 2.53 | 66.45 | 3.38 | 87.51 |
| 26 | 28.12 | 19.71 | 9.94 | 3.19 | 69.64 | 3.85 | 91.36 |
| 27 | 33.39 | 17.44 | 9.64 | 3.25 | 72.89 | 4.04 | 95.40 |
| 28 | 30.28 | 15.87 | 9.38 | 2.61 | 75.50 | 3.34 | 98.74 |

**Table D-2. Example of a probabalistic trial for concrete slabs.**

| Piece No. | Length (in.) | Width (in.) | Height (in.) | Volume ($ft^3$) | Cumulative Volume ($ft^3$) | Area ($ft^2$) | Cumulative Area ($ft^2$) |
|---|---|---|---|---|---|---|---|
| 29 | 25.97 | 18.51 | 7.92 | 2.20 | 77.71 | 3.34 | 102.08 |
| 30 | 31.11 | 16.80 | 7.06 | 2.13 | 79.84 | 3.63 | 105.71 |
| 31 | 13.91 | 15.17 | 9.61 | 1.17 | 81.02 | 1.47 | 107.17 |
| 32 | 31.47 | 17.01 | 9.60 | 2.97 | 83.99 | 3.72 | 110.89 |
| 33 | 24.30 | 18.60 | 8.63 | 2.26 | 86.24 | 3.14 | 114.03 |
| 34 | 24.48 | 15.15 | 8.56 | 1.84 | 88.08 | 2.57 | 116.60 |
| 35 | 32.01 | 16.63 | 8.18 | 2.52 | 90.60 | 3.70 | 120.30 |
| 36 | 35.38 | 19.53 | 8.94 | 3.57 | 94.18 | 4.80 | 125.10 |
| 37 | 26.09 | 17.38 | 9.10 | 2.39 | 96.56 | 3.15 | 128.25 |
| 38 | 24.83 | 18.74 | 8.98 | 2.42 | 98.98 | 3.23 | 131.48 |
| 39 | 25.64 | 17.60 | 8.83 | 2.31 | 101.29 | 3.13 | 134.61 |
| 40 | 34.15 | 15.56 | 6.84 | 2.10 | 103.39 | 3.69 | 138.30 |
| 41 | 32.66 | 18.93 | 8.04 | 2.88 | 106.27 | 4.29 | 142.60 |
| 42 | 26.27 | 20.42 | 8.14 | 2.53 | 108.80 | 3.73 | 146.32 |
| 43 | 36.14 | 13.84 | 9.27 | 2.68 | 111.48 | 3.47 | 149.79 |
| 44 | 34.36 | 16.29 | 9.15 | 2.97 | 114.44 | 3.89 | 153.68 |
| 45 | 30.35 | 16.34 | 9.36 | 2.69 | 117.13 | 3.44 | 157.13 |
| 46 | 31.13 | 16.24 | 9.10 | 2.66 | 119.79 | 3.51 | 160.64 |
| 47 | 22.64 | 16.54 | 10.82 | 2.34 | 122.14 | 2.60 | 163.24 |
| 48 | 23.14 | 17.60 | 8.29 | 1.96 | 124.09 | 2.83 | 166.07 |
| 49 | 25.20 | 21.90 | 9.07 | 2.90 | 126.99 | 3.83 | 169.90 |
| ***50*** | 20.81 | 19.20 | 8.99 | 2.08 | ***129.07*** | 2.77 | ***172.67*** ** |

** For this trial and with a concrete density of 150.0 lbs/$ft^3$, then 9.68 tons of concrete (approximately 50 pieces) are needed to cover 1% of a module.

**Table D-3. Average of six probabistic Trials to estimate amount of concrete required for each coverage.**

| Percentage of Cover | Tons | Tons per Acre | No. of Pieces |
|---|---|---|---|
| 1% | 9.15 | 23.5 | 50 |
| 17% | 156 | 399 | 850 |
| 34% | 311 | 797 | 1700 |
| 67% | 613 | 1,571 | 3350 |

**Table D-4. Example of a probabalistic trial for rock.**

| Piece No. | Length (in.) | Width (in.) | Height (in.) | Volume ($ft^3$) | Cumulative Volume ($ft^3$) | Area ($ft^2$) | Cumulative Area ($ft^2$) |
|---|---|---|---|---|---|---|---|
| 1 | 11.16 | 10.30 | 5.17 | 0.27 | 0.27 | 0.63 | 0.63 |
| 2 | 25.52 | 25.04 | 11.03 | 3.20 | 3.47 | 3.49 | 4.11 |
| 3 | 25.10 | 14.89 | 14.02 | 2.38 | 5.86 | 2.04 | 6.15 |
| 4 | 22.02 | 14.15 | 15.31 | 2.17 | 8.02 | 1.70 | 7.85 |
| 5 | 17.75 | 17.01 | 14.23 | 1.95 | 9.98 | 1.65 | 9.50 |
| 6 | 25.06 | 19.40 | 15.54 | 3.43 | 13.41 | 2.65 | 12.15 |
| 7 | 22.62 | 17.68 | 13.22 | 2.40 | 15.81 | 2.18 | 14.33 |
| 8 | 15.68 | 22.61 | 15.59 | 2.51 | 18.33 | 1.93 | 16.26 |
| 9 | 23.30 | 24.61 | 12.31 | 3.21 | 21.53 | 3.13 | 19.39 |
| 10 | 25.66 | 17.41 | 10.86 | 2.21 | 23.74 | 2.44 | 21.83 |
| 11 | 33.34 | 23.04 | 17.69 | 6.18 | 29.91 | 4.19 | 26.02 |
| 12 | 30.10 | 21.41 | 16.29 | 4.77 | 34.68 | 3.52 | 29.53 |
| 13 | 26.87 | 17.03 | 8.90 | 1.85 | 36.54 | 2.50 | 32.03 |
| 14 | 19.80 | 19.22 | 10.29 | 1.78 | 38.32 | 2.07 | 34.10 |
| 15 | 22.52 | 13.89 | 14.51 | 2.06 | 40.38 | 1.71 | 35.81 |
| 16 | 26.94 | 15.95 | 14.97 | 2.92 | 43.30 | 2.34 | 38.15 |
| 17 | 20.65 | 13.87 | 16.30 | 2.12 | 45.43 | 1.56 | 39.72 |
| 18 | 23.94 | 13.93 | 13.55 | 2.05 | 47.48 | 1.82 | 41.54 |
| 19 | 24.02 | 18.23 | 13.50 | 2.69 | 50.16 | 2.39 | 43.92 |
| 20 | 14.75 | 19.42 | 12.12 | 1.58 | 51.74 | 1.56 | 45.49 |
| 21 | 32.41 | 16.12 | 13.53 | 3.21 | 54.96 | 2.85 | 48.34 |
| 22 | 26.84 | 15.41 | 13.85 | 2.60 | 57.56 | 2.26 | 50.59 |
| 23 | 27.89 | 15.83 | 14.13 | 2.83 | 60.39 | 2.41 | 53.00 |
| 24 | 19.52 | 16.93 | 13.32 | 2.00 | 62.39 | 1.80 | 54.80 |
| 25 | 18.84 | 18.32 | 7.99 | 1.25 | 63.65 | 1.88 | 56.68 |
| 26 | 29.34 | 15.35 | 12.78 | 2.62 | 66.26 | 2.46 | 59.14 |
| 27 | 23.35 | 14.47 | 14.65 | 2.25 | 68.51 | 1.84 | 60.98 |
| 28 | 19.21 | 18.91 | 9.91 | 1.64 | 70.15 | 1.98 | 62.96 |
| 29 | 26.16 | 11.66 | 11.04 | 1.53 | 71.68 | 1.66 | 64.63 |
| 30 | 21.66 | 23.26 | 13.05 | 2.99 | 74.67 | 2.75 | 67.37 |
| 31 | 17.34 | 15.05 | 10.73 | 1.27 | 75.94 | 1.42 | 68.80 |
| 32 | 22.19 | 12.67 | 13.72 | 1.75 | 77.69 | 1.53 | 70.33 |
| 33 | 26.41 | 14.62 | 12.91 | 2.27 | 79.96 | 2.11 | 72.44 |
| 34 | 17.29 | 20.90 | 13.58 | 2.23 | 82.19 | 1.97 | 74.41 |
| 35 | 21.21 | 20.59 | 11.64 | 2.31 | 84.50 | 2.38 | 76.79 |
| 36 | 28.85 | 20.16 | 14.59 | 3.86 | 88.36 | 3.17 | 79.96 |
| 37 | 23.19 | 17.78 | 13.08 | 2.45 | 90.81 | 2.25 | 82.21 |
| 38 | 26.77 | 14.81 | 12.97 | 2.34 | 93.14 | 2.16 | 84.37 |

**Table D-4. Example of a probabalistic trial for rock.**

| Piece No. | Length (in.) | Width (in.) | Height (in.) | Volume ($ft^3$) | Cumulative Volume ($ft^3$) | Area ($ft^2$) | Cumulative Area ($ft^2$) |
|---|---|---|---|---|---|---|---|
| 39 | 23.77 | 18.70 | 14.79 | 2.99 | 96.13 | 2.42 | 86.80 |
| 40 | 18.37 | 16.92 | 13.79 | 1.95 | 98.08 | 1.70 | 88.49 |
| 41 | 27.28 | 19.49 | 14.12 | 3.41 | 101.49 | 2.90 | 91.39 |
| 42 | 31.21 | 17.21 | 18.14 | 4.43 | 105.92 | 2.93 | 94.32 |
| 43 | 13.84 | 14.12 | 10.07 | 0.89 | 106.82 | 1.07 | 95.39 |
| 44 | 20.30 | 18.48 | 6.44 | 1.10 | 107.91 | 2.05 | 97.43 |
| 45 | 20.43 | 20.32 | 11.74 | 2.21 | 110.13 | 2.26 | 99.70 |
| 46 | 20.18 | 19.52 | 10.67 | 1.91 | 112.04 | 2.15 | 101.85 |
| 47 | 20.98 | 16.72 | 12.22 | 1.95 | 113.98 | 1.91 | 103.76 |
| 48 | 23.77 | 20.00 | 8.70 | 1.88 | 115.86 | 2.59 | 106.35 |
| 49 | 35.12 | 18.36 | 10.45 | 3.06 | 118.93 | 3.52 | 109.87 |
| 50 | 27.98 | 17.58 | 9.99 | 2.23 | 121.16 | 2.68 | 112.55 |
| 51 | 20.79 | 20.28 | 11.50 | 2.20 | 123.36 | 2.30 | 114.85 |
| 52 | 23.83 | 17.33 | 11.80 | 2.21 | 125.58 | 2.25 | 117.10 |
| 53 | 26.60 | 16.51 | 18.80 | 3.75 | 129.33 | 2.40 | 119.50 |
| 54 | 20.35 | 20.40 | 11.88 | 2.24 | 131.57 | 2.26 | 121.76 |
| 55 | 29.66 | 19.55 | 13.31 | 3.51 | 135.08 | 3.16 | 124.93 |
| 56 | 33.37 | 11.49 | 7.78 | 1.35 | 136.44 | 2.09 | 127.02 |
| 57 | 23.85 | 16.94 | 10.96 | 2.01 | 138.45 | 2.20 | 129.22 |
| 58 | 25.47 | 19.31 | 14.92 | 3.33 | 141.78 | 2.68 | 131.90 |
| 59 | 29.79 | 18.76 | 11.92 | 3.03 | 144.81 | 3.05 | 134.95 |
| 60 | 26.91 | 15.10 | 13.31 | 2.46 | 147.27 | 2.22 | 137.17 |
| 61 | 23.63 | 15.27 | 16.28 | 2.67 | 149.93 | 1.97 | 139.13 |
| 62 | 23.72 | 14.94 | 15.22 | 2.45 | 152.39 | 1.93 | 141.07 |
| 63 | 22.93 | 16.11 | 9.63 | 1.62 | 154.00 | 2.01 | 143.08 |
| 64 | 14.11 | 12.80 | 8.19 | 0.67 | 154.68 | 0.98 | 144.07 |
| 65 | 32.79 | 16.16 | 13.56 | 3.27 | 157.94 | 2.89 | 146.96 |
| 66 | 22.16 | 13.06 | 13.99 | 1.84 | 159.78 | 1.58 | 148.54 |
| 67 | 19.40 | 19.25 | 10.58 | 1.80 | 161.58 | 2.04 | 150.57 |
| 68 | 22.85 | 20.74 | 10.82 | 2.33 | 163.91 | 2.58 | 153.16 |
| 69 | 23.68 | 21.83 | 11.27 | 2.65 | 166.56 | 2.82 | 155.98 |
| 70 | 29.72 | 20.27 | 14.45 | 3.96 | 170.52 | 3.29 | 159.26 |
| 71 | 21.62 | 19.49 | 9.61 | 1.84 | 172.36 | 2.30 | 161.56 |
| 72 | 24.96 | 22.09 | 10.60 | 2.66 | 175.01 | 3.01 | 164.57 |
| 73 | 19.20 | 17.71 | 15.58 | 2.41 | 177.42 | 1.85 | 166.42 |
| 74 | 17.66 | 19.98 | 12.38 | 1.98 | 179.41 | 1.92 | 168.35 |
| ***75*** | 25.94 | 23.14 | 10.46 | 2.85 | ***182.26*** | 3.27 | ***171.62**** |

** For this trial and with a rock density of 169.75 lbs/$ft^3$, then 15.47 tons of concrete (approximately 75 pieces) are needed to cover 1% of a module.

**Table D-5. Average of six probabistic trials to estimate amount of rock required for one module of each coverage type.**

| Percentage of Cover | Tons | Tons per Acre | No. of Pieces |
|---|---|---|---|
| 1% | 15.02 | 38.47 | 76 |
| 17% | 255 | 654 | 1,292 |
| 34% | 511 | 1,308 | 2,584 |
| 67% | 1,006 | 2,578 | 5,092 |

# APPENDIX E.
# WORST-CASE WEIGHTS OF EXPERIMENTAL SUBSTRATE

To establish an upper bound for material quantities, a worst case was considered. Round stones and relatively thick pieces of concrete would be the least efficient use of material. This method assumes that these geometrically undesirable materials are used.

The average undesirable rock would have an angularity about 20-30% worse than the measured rock pieces. Also, the rocks, being rounded, are assumed to roll off of each other, and therefore not pile up in clumps. Consequently no loss factor for overlap is assigned. The average undesirable concrete slab would have a height of 15 in. Since these pieces are flat and slab-like, it was assumed that placement methods would result in some slabs overlapping. Therefore, a reasonable worst-case value of 15% was estimated as waste material because of overlap.

To calculate the number of pieces needed, we divided the square footage of bottom coverage desired by the surface area; then we multiplied the number of pieces by the average weight to calculate the tonnage required. The quantity results for this worst case are 22,074 tons of rock and 20,354 tons of concrete.

## Calculations for Rock

- Undesirable rocks have the following averaged dimensions:

| | | |
|---|---|---|
| Length (l) | = | 24 in. |
| Width ($w$) | = | 18 in. |
| Height ($h$) | = | 15 in. |

- Pieces have about 30% less Angularity than the measured pieces:

| | | | | | |
|---|---|---|---|---|---|
| Angularity of worst-case piece | = 2.13 | | Ratio of ($w/h$) | = | 1.20 |
| Angularity of measured sample | = 2.83 | | Ratio of ($w/h$) | = | 1.15 |

- Then, an average undesirable piece has:

| | | |
|---|---|---|
| Area | = | 2.36 $ft^2$ |
| Volume | = | 2.95 $ft^3$ |
| Weight | = | 500 lbs |

- To achieve different coverages per module:

| | | | | | | |
|---|---|---|---|---|---|---|
| Low Coverage | = | 1,411 pieces | = | 705,378 lbs | = | 353 tons |
| Medium Coverage | = | 2,822 pieces | = | 1,410,755 lbs | = | 705 tons |
| High Coverage | = | 5,561 pieces | = | 2,780,018 lbs | = | 1,390 tons |

**Table E-1. Calculation table for total tonnage of rock needed for an undesirable case.**

| Coverage | No. Modules | Tons/Acre | Total Tonnage |
|---|---|---|---|
| Low (17%) | 7 | 903 | 2,469 |
| Medium (34%) | 14 | 1,807 | 9,875 |
| High (67%) | 7 | 3,561 | 9,730 |
| **Total for Experimental Reef** | **28** | **n/a** | **22,074** |

## Calculations for Concrete

- Undesirable concrete pieces are considered a prism with an average height of 15 in.
- An average undesirable piece has:

  Area = 1.00 $ft^2$
  Volume = 1.25 $ft^3$
  Weight = 187.5 lbs

- To achieve different coverages per module (assuming placement is poor and about 15% bottom coverage is lost because of overlapping:

  Low Coverage = 3,469 pieces = 650,409 lbs = 325 tons
  Medium Coverage = 6,938 pieces = 1,300,818 lbs = 650 tons
  High Coverage = 13,671 pieces = 2,563,377 lbs = 1,282 tons

**Table E-2. Calculation table for total tonnage of concrete needed for the worst case.**

| Coverage | No. Modules | Tons/Acre | Total Tonnage |
|---|---|---|---|
| Low (17%) | 7 | 833 | 2,276 |
| Medium (34%) | 14 | 1,666 | 9,106 |
| High (67%) | 7 | 3,283 | 8,972 |
| **Total for Experimental Reef** | **28** | **n/a** | **20,354** |