

The Impact of Bleaching on Coral Strength

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Abstract

Coral bleaching results in degradation of the organism's health. As such, this study set out to identify and determine the extent to which coralline health correlates to coralline strength. Healthy and bleached coral samples were collected at sites in Kiribati and Palmyra. Samples were stressed uniaxially with controlled weight increase until fracture, obtaining the critical fracture mass and thereby the tensile stress (strength) of the samples. The measurement data does not demonstrate a definitive trend regarding the impact of bleaching on the mechanical properties of coral due to a variability that can be attributed to the lack of a solid baseline with which to compare coral strength. Significant variations occurred on the intra-colony and inter-colony levels as well as between different sites and different species. These variations occur given coralline construction in response to environmental requirements. In order to identify the impact of bleaching on strength, if any, a baseline mechanism of comparison must be developed to take into account variation within colonies. Though this study does not provide that baseline, it serves as evidence and impetus for the necessity of creating a baseline from which to assess the impact of coralline health on its strength and thereby the viability/survivability of the entire reef ecosystem.

Introduction

In 1984, Glynn was the first to describe coral bleaching affecting extensive reef areas across the Pacific. Since then, the whitening of corals due to the loss of symbiotic algae (zooxanthellae) and/or their pigments has been identified in reefs around the world. Researchers have identified several causes for coral bleaching, almost all of which are the direct effect of global climate change: causes include fluctuations in seawater temperature, solar radiation, reduced salinity, and combinations thereof. (Brown et al. 1996) The loss in health and stability due to coral bleaching goes beyond the disappearance of a major source of nutrition and color – tissue growth, skeletal accretion, and sexual reproduction are suspended as well. In areas where the stress (weakening) from bleaching leads to coral mortality, the raised probability of the reef breaking down due to its increased vulnerability and the resulting loss of an ecosystem makes coral bleaching a tremendous event. While it has been theorized that as some corals and their zooxanthellae recover, they may become more stress-tolerant, there is little evidence that this occurs and rather research has shown that the physiological and metabolic stress further increases susceptibility to the effects of future stress events. (Reaser et al. 2000) In 1985, Brown and Howard reviewed seven accepted measures of coral health: 1) growth rate; 2) metabolism; 3) biochemistry; 4) reproduction; 5) behavioral response; 6) disease; or 7) loss of zooxanthellae. Holden and LeDrew (1998) used the latter in objectively measuring and determining coral health. They implemented a spectroradiometer and derivative analysis to reveal that there is a

spectral distinction between healthy and bleached coral based primarily on the magnitude of reflectance – this distinction exists as light waves, normally absorbed by the zooxanthellae, is reflected. Assessing the extent to which this difference, vis a vi the degradation in coral health, impacts tensile strength (biomechanical properties) would be critical to understanding the overall effect of coral bleaching on coral strength and more largely, the long-term viability of the reef ecosystem.

Biomechanical theory predicts that resistance to mechanical injury should be determined by the morphological properties of coral colonies – this theory was tested in 2000 by Marshall on the Great Barrier Reef, where he determined a relationship between resistance and the structural variables of colony height, branch thickness, branch spacing, and colony area. Interestingly, he determined that skeletal density was relatively unimportant in determining susceptibility to breakage – strongly contradicting earlier work emphasizing density as an explanation for variation in the resistance of corals (Chamberlain 1978). A factor that could account for this disparity is the impact of zooxanthellae on coral strength: these organisms symbiotically live in, and vitally function in the health of, the coral tissue. It has long been believed that given a skeleton made of a particular material, there are two things that will have a significant effect on its strength and stiffness: grain size and porosity. Furthermore, it has been demonstrated that a skeleton with many voids is weaker than a solid one. Speculation arises as to why animals, specifically corals in this case, would build such a skeleton given the implicit weakening: Wainwright et al.'s solution to this question is that the pores serve a function by increasing the area possible for symbiotic organisms to live in. While noting that organisms fill the pores, Wainwright et al. fail to take into account the impact that these organisms have upon the strength of the resulting healthy coral. The principal objective of this study was to determine if and to what extent zooxanthellae has an impact upon coral strength. The impact theoretically seems plausible as the healthy tissue could serve as a reinforcer, absorbing stress that would otherwise propagate through the pores and cause fracture – yet another benefit in the symbiotic relationship as zooxanthellae positively affect tissue health via nourishment. Alternatively and more probable given the thin and delicate nature of coral tissue, the zooxanthellae may play a role in influencing coral strength in that their photosynthetic activity facilitates deposition of CaCO_3 – when this activity ceases, the skeleton may be weakened, as CaCO_3 losses are not compensated by new deposition. By comparing the tensile strength (stress required for fracture) of healthy

and non-healthy coral, the correlation between coral health and its resistance to mechanical stress can be determined. This implication of coral health would be tremendous evidence to the damage coral bleaching truly has on a reef's sustainability.

Methods and Materials

Branching coral with pieces of uniform radii were selected for use in the study: the species found at sampling locations that satisfied this basic requirement were *Pocillopora eydouxi* at Kiribati, *Acropora formosa* and *Acropora nobilis* at Palmyra Atoll (it should be noted that the *Acropora* species were more abundant in providing samples of uniform radii, while relatively few colonies/morphologies of the *Pocillopora eydouxi* had digitate extensions). When possible, multiple samples from the same colony were collected with the goal of consistency in colony strength. Due to the limited number of *Pocillopora eydouxi* samples of uniform shape at the dive sites visited, samples from the same colony were not collected and few samples were collected overall in Kiribati. The two species of *Acropora* are commonly found together and, due to the significant similarity in their appearance, were indistinguishable in this study. Four samples of *eydouxi* were collected from the Bay of Wrecks on Christmas Island and 30 total samples of *Acropora* were collected at Palmyra – 15 respectively from Tiger Shark Point and North of the Channel. Coral samples were also selected for their health level (healthy and bleached) with the overall good reef health limiting the number of bleached samples collected. Following collection by free diving, the samples were stored in seawater until measured – within a day of removal from the reef – though there was some degradation and sloughing of the coral tissue by the time the samples were tested. Measurements were conducted on land to ensure a stable environment and perpendicular force.

Measurement of tensile stress (strength). Using a setup roughly shown in Figure 1, the force required for fracture is calculated from the critical load at fracture. Essentially, a load is placed on the coral sample in a sectional area of equal radius evenly spaced on the loaded region (the region balanced between the two triangles); when the sample fractures, that critical load is measured. Given that $F = ma$, where m is the weight needed for fracture and a is the force of gravity (that is, 9.81 m/s^2), we can calculate the fracture force. Once we know the fracture force, we can calculate the stress required for breakage (the strength) of the material with the following equation (Denny):

$$\sigma_b = Mz/I = F*l*r/(\pi*r^4/4) = 4*F*l/(\pi*r^3) \quad (1)$$

where z is the half-depth of the beam (coral), r is the radius of the sample, l is the length from the weight area to the balance point, M is the moment, I is the second moment of area, and

$$z = r \quad (2)$$

$$M = F*l \quad (3)$$

$$I = \pi*r^4/4 \quad (4)$$

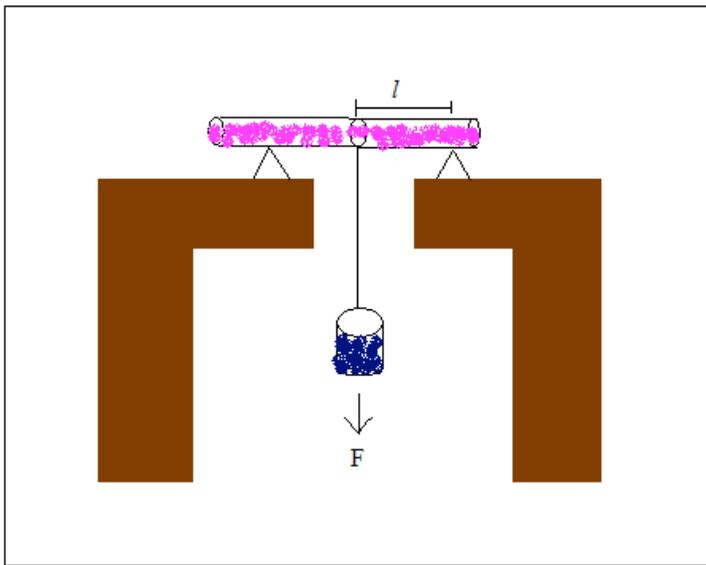


Figure 1: Rough diagram of design of device used to measure Force required for fracture

Results

Using the aforementioned methodology, I measured the critical fracture stress (mechanical strength) for 34 collected samples. The results are summarized in Tables 1 and 2 for the Kiribati and Palmyra samples, respectively. Because of the limited number of Pocillopora (Kiribati) samples collected, I will primarily focus on the results of the Acropora (Palmyra) samples as the larger number of samples enables more robust results and discussion. However, even with a limited number of Pocillopora samples, we still see a variation in the strength, an inability to distinguish the bleached samples as having a strictly higher or lower strength, and a higher mean strength compared to Acropora.

Christmas, Kiribati					
Species: <i>Pocillopora eydouxi</i>					
Sample	Radius (cm)	Length (cm)	Fracture Weight (kg)	Bleached	Strength (MPa)
1	0.65	4.4	39.90	0	79.85
2	0.65	5.5	32.97	0	82.47
3	0.8	4.9	52.91	1	63.25
4	0.55	4.4	35.20	1	116.28
mean					85.46
std. dev.					22.24

Table 1: Data from Kiribati samples including sample radius, length, fracture weight, bleached, and strength.

Palmyra Atoll - Tigershark Point (Colonies 1-6) and North of Channel (Colonies 7-12)								
Species: <i>Acropora formosa</i> / <i>Acropora nobilis</i>								
Sample	Radius (cm)	Length (cm)	Fracture Weight (kg)	Colony	Bleached	Strength (MPa)	Ave. Strength/Colony	Std. Dev./Colony
1a	0.75	5.75	36.20	1	0	61.63	78.23	14.84
1b	0.60	4.50	31.85	1	0	82.88		
1c	0.60	4.25	36.70	1	1	90.19		
2a	0.40	4.00	7.42	2	1	57.92	42.92	21.22
2b	0.65	4.20	14.61	2	0	27.91		
3a	0.50	4.10	12.99	3	1	53.22	40.68	8.51
3b	0.45	2.65	9.95	3	0	36.14		
3c	0.45	1.50	16.90	3	1	34.75		
3d	0.48	1.90	17.43	3	0	38.60		
4a	0.35	2.90	7.79	4	0	65.81	65.81	
5a	0.65	4.90	16.47	5	0	36.71	43.75	7.34
5b	0.60	4.50	16.60	5	0	43.20		
5c	0.55	4.50	15.20	5	0	51.35		
6a	0.45	4.10	16.40	6	1	92.17	74.47	25.03
6b	0.60	4.25	23.10	6	1	56.77		
21a	0.50	2.00	9.58	7	0	19.15	34.32	21.47
21b	0.40	1.90	13.35	7	0	49.50		
22a	0.45	4.25	9.53	8	0	55.52	55.52	
23a	0.50	4.25	13.73	9	0	58.31	71.10	17.09
23b	0.45	4.20	11.20	9	0	64.48		
23c	0.45	4.15	15.91	9	0	90.50		
24a	0.30	4.00	6.48	10	0	119.91	83.28	33.54
24b	0.35	1.60	11.60	10	0	54.07		
24c	0.28	1.55	8.15	10	0	75.87		
25a	0.30	4.18	8.00	11	0	154.51	143.84	15.09
25b	0.30	1.75	16.45	11	0	133.17		
26a	0.50	4.20	15.31	12	1	64.25	75.41	20.81
26b	0.30	2.40	7.50	12	0	83.27		
26c	0.40	2.10	13.06	12	1	53.53		
26d	0.40	2.15	23.97	12	0	100.58		
Mean						66.86		
Std. Dev.						31.02		

Table 2: Data from Palmyra samples including sample radius, length, fracture weight, colony source, bleached, strength, average strength per colony and standard deviation of strength per colony.

Figure 2 shows the average strength per colony along with the standard deviation above and below that mean for the 30 samples collected at Palmyra – Colonies 1-6 correspond to increasingly higher wave energy areas at Site 1: Tiger Shark Point; Colonies 7-12 existed in energetically similar areas at Site 2: North of the Channel. Though Site 1 had higher wave energy compared to Site 2, the mean strength of the former was lower than that of the latter, 55.28 MPa versus 78.44 MPa (68.38 MPa without the outliersque samples from Colony 11).

A trend was observed whereby the samples seem to fit around two distinct means instead of one overall mean. The mean of the 30 samples is 66.86 MPa with a standard deviation of 31.02; alternatively, if we remove Colony 11 and lump the other colonies into two groups, the means of these two groups of samples become 75.89 MPa and 42.00 MPa with standard deviations of 19.24 and 11.89, respectively. These two means are shown in Figure 2 as horizontal red lines.

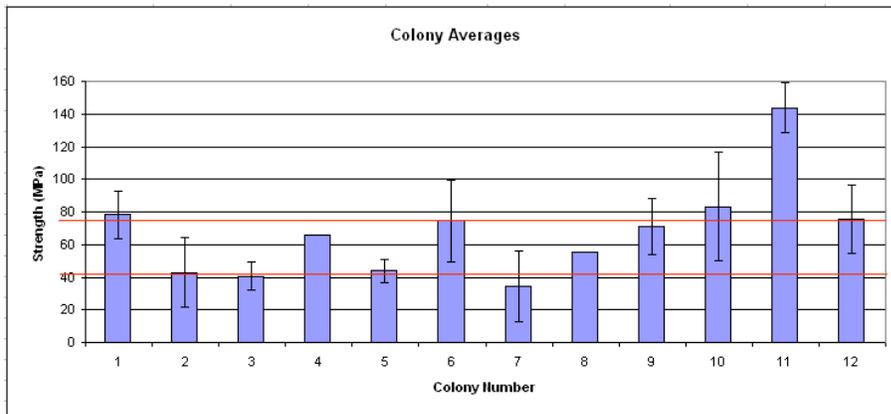


Figure 2: Graph of the mean and standard deviation of colony strengths from 30 samples collected at Palmyra.

Figure 3 displays the individual sample strengths that collectively create the colony averages shown in Figure 2. Of note is the significant variation within colonies, with a maximum standard deviation of 33.54 in Colony 10 and a minimum standard deviation of 7.34 in Colony 5. Additionally Figure 3 distinguishes between the bleached and healthy samples (bleached data points highlighted with a box). The bleached samples do not have an overall trend of reduced strength as previously postulated, and are also subject to strength variation within and amongst colonies.

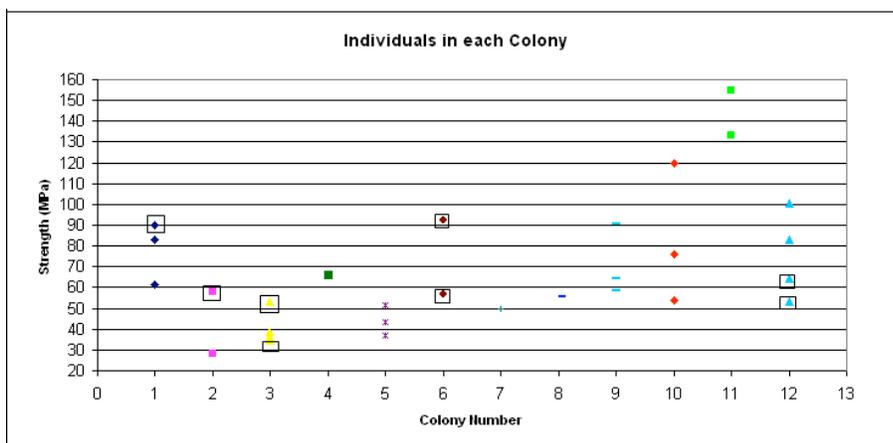


Figure 3: Graph of strength of individual samples grouped by colony source – bleached are distinguished with a box around the sample.

Discussion

In setting out to do this study, I was primarily concerned with the impact bleaching would have on coral strength based on the following simplified rationale: bleaching equals unhealthy, unhealthy equals weaker, therefore bleaching equals weaker. Yet the bleached samples showed no trend of lower strength. While some samples do follow this anticipated trend, there are also

samples that follow the opposite and are actually stronger than their healthy neighbors. So I am led to question why the data is consistently all over the place, assuming minimal measurement errors arising from standardized techniques: three observations and potential sources for disparity arise, 1) there is a significant variation within the material strength of samples from the same and different colonies, 2) there appears to be two mean strengths (for the Palmyra samples) that could correspond to the mechanical strengths of the two *Acropora* species, and 3) there is a significant difference in the coral strengths at the two sampling sites in Palmyra.

When designing this experiment, I tried to achieve accuracy/stability by testing multiple samples from the same colony, with the preconception that a staghornlike coral would have fairly uniform strength among its branches. However, the data shows a very different picture – that is, there is significant variation within sample strengths from the same colony. While at first perplexing, this observation makes sense given that colonies can change their morphology in response to the wave energy of their environment. It follows that the organisms should be able to distribute their resources to minimize expenditure of energy – that is, the coral constructs itself by sparingly expending energy on lower wave force faces while strengthening higher wave force faces. While beyond the scope of the data collection performed for this study, it would be tremendously interesting to create a 3D mapping of a coral colony as put together by samples from all over the colony – top, bottom, leeward, windward, and gradients in between. Successful organisms are renowned for minimizing energy expenditure while maximizing stability and survival: to see this concept carried out on in the framework of the coral's mechanical/material construction properties would provide evidence for the mechanism corals use to construct the reefs that serve as ecosystems on a grand scale. Additionally, this could account for the inconclusiveness of the bleaching and intra-colony data – we can only identify if a deterioration in mechanical strength accompanies bleaching events by comparing samples and colonies subject to the same forces.

A particularly compelling reason for inter-colony variation in strengths could be that the samples came from two species of *Acropora* – *Acropora formosa* and *Acropora nobilis* – and that the two species have different strengths. A 2-tailed homoscedastic T-test of the samples that are believed to be two distinct species – a grouping of all the samples except those of colony 11 – shows that the probability of there being two distinct groups (species) is 96.1%. Though visually very similar and commonly existing together on reef slopes and lagoons, they have differing

corallite structures (*formosa* has tubular radial corallites and *nobilis* has rasp-like radial corallites) and likely some skeletal structural differences as well. While a more thorough examination of the structures is required to specifically identify the differences that could allow for the strength variation, my precursory hypothesis is that the *formosa*'s tubular corallites provide more structural support than the *nobilis*' rasp-like corallites.

Another potential source for inter-colony variation in strength could be the impact of site. For ease and functionality, coral reefs are commonly classified by their oceanic location, i.e. reef slope, lagoon, barrier, fringing, etc. This classification does not take into account the extreme variation within these marine environments – a function of the multitude of factors that affect specific reef composition. Both Site 1 and Site 2 are fringing reefs, yet the samples vary in their strength (fracture stress). A 2-tailed homoscedastic T-test of the samples from the two sites yields a probability of being two distinct groups of 99.999%. A confusing observation about the data from the two sites is though the energetic difference would suggest that Site 1 should have a higher mean than Site 2, in fact the opposite occurred (55.28 MPa versus 78.44 MPa). I can only attribute this disparity to additional factors, including but certainly extending well beyond intra-colony variation and the possibility of two species.

As a final caveat, I draw attention to the strength difference between *Pocillopora eydouxi* and the *Acropora* species. *Pocillopora eydouxi* thrives on exposed reef fronts where currents are strong. Conversely, the *Acropora* species are common on reef slopes and lagoons (energetically lower regions than reef fronts). As such, it would follow that *Pocillopora* is a heartier coral with greater mechanical strength than *Acropora*. The data concurs, yielding mean strengths of 85.46 MPa and 66.86 MPa (75.89 MPa and 42.00 MPa believed to be the two *Acropora* species). Though not necessarily a surprising result, it is interesting to be able to assign a number to the increased strength necessary to survive in energetically higher environments.

The limited number of samples (on the level of species and health) is certainly a restriction, and while the trends observed are suggestive, a more conclusive study requires greater sampling. Measurements were standardized per location, with variation between the measurements made at Kiribati and those made at Palmyra minimized, and correspondingly so with the errors. The limited number of collected samples was in part a result of reef locations being either too healthy or too unhealthy. Of the 10 sites visited, only three were conducive to sample collecting and measuring – some of the reefs were limited to coral morphologies

immeasurable by my methods, a couple were almost totally dead and destroyed, and a couple were pristine to the extent of precluding bleached corals.

Conclusion

Coral bleaching plays a significant role in the deterioration of reefs and thus the entire reef ecosystem. Bleached reefs have widely been recognized as unhealthy – more susceptible to destruction from storms, disease, and invasive/boring algae. But to what extent are these reefs weaker? If coral colonies are more easily broken and swept away after bleaching events, I would expect to see a material/mechanical degradation to attribute to this trend. A loss in mechanical strength, to go along with the loss of zooxanthellae that characterizes bleaching events, seems particularly compelling – an unhealthy organism should be a weaker one. Yet, when I review my data, this is not the case.

I collected 24 samples of healthy coral and 10 samples of bleached coral from three dive locations (one at the Bay of Wrecks on Christmas Island and two near the channel at Palmyra Atoll). Having obtained my data, I have not been able to identify a consistent trend of bleached coral being weaker. The factors which I believe have compounded to create this disparity include intra and inter-colony strength variation in part stemming from structural, species, and site differences. If these factors were normalized via increased and more robust sampling, perhaps the expected decrease in strength could be observed.

Corals construct themselves to maximize stability and survival while minimizing expenditure of energy. They alter colony morphology, adapting to their surroundings; it follows that they should be able to alter how strong they construct differing segments as well. By mapping the strength of a colony on its differing faces, perhaps we can achieve a stable baseline from which to more fully view the impact of health and location on coral strength and survival. Corals serve a tremendous and complicated role in their ecosystem – understanding more details about the mechanical properties of the coral that dictate their structure and limitations is critical to understanding their function in the reef ecosystem.

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