Mix design and properties of coral aggregate concrete for Oceania islands

Tatheer Zahra[1]
[1]Lecturer of Civil Engineering, Queensland University of Technology (QUT)

Abstract: Manufacturing concrete with coral gravel and coral sand as aggregates is of great significance for the construction in islands due to shortage of conventional aggregates. Research in this area is very scarce and mix design guidelines are not available for the concrete manufacturers and constructors. This paper presents mix design proportions and mechanical properties of concrete mixes containing coral aggregate obtained from an Oceania island. The properties of aggregates were measured in the lab to develop a mix design for 25MPa concrete strength which is commonly used in low rise and medium rise buildings. Stress-strain curves, modulus of elasticity and strength of coral concrete for the batched cylinders manufactured according to the proposed mix design are reported. An average strength of 27MPa was determined for the trial mix. The mix design for various other strengths of coral aggregate concrete was then developed. The findings of this research are useful for the designers and contractors of Oceania islands.

Keywords: Coral aggregate concrete, Coral aggregates, Mix proportion design, Cementitious materials, Compressive strength, Mechanical properties.

1. Introduction

Coral aggregates are used to make concrete in the islands for their abundant availability as compared to conventional aggregates. However, the research in the area of coral aggregate concrete including strength, durability and mix design is very limited. Builders in the small islands of Oceania such as in Vanuatu and Palau use the mix proportions for coral aggregate concrete based on their experience as the properties of coral sand and gravel and their effects on the concrete are not well known. Hence, development of a proper mix design proportion for coral aggregate concrete is of paramount importance.

Available research in the field of coral concrete is still very preliminary. Most of the research has been conducted by Chinese researchers for the corals used in concrete in reclamation projects for Chinese islands. Wang et al. (2018) observed that coral aggregates have rough surface and porous structure, and these features seriously affect the workability, mechanical property, failure mode and durability of coral concrete. Additionally, because of these features, the normal aggregate concrete mix design procedure is not always suitable for coral aggregate concrete. To manufacture durable coral concretes which can survive in the ocean environment with high concentrations of chloride, magnesia and sulphate ions and varying temperatures, the use of cementitious compounds such as fly ash, silica fume, slag and fibers was shown useful (Wang et al. 2018; Wu et al. 2018; Wang et al. 2019).

The strength grade of coral concrete is relatively low, about 30MPa or lower, which could be increased by increasing the cement content or by adding superplasticizers, while the properties of coral concrete are somewhere between that of lightweight aggregate concrete and that of normal concrete (Liu at al 2018). The failure pattern of coral aggregate concrete is brittle because of the porous coral aggregates in comparison to natural and recycled aggregate concretes which are relatively ductile (Huang et al, 2018). Moreover, pre-wetted coral aggregate can gradually release the water absorbed before and during the cement hydration process, enhancing the interface bonding between aggregate and cement matrix (Zhou et al, 2019). By reducing the amount of coral gravel and blending of micro-coral sand and coral sand, an ultra-high-performance concrete (UHPC) can be developed which was shown to have better durability against chloride and sulphate attacks (Wang et al, 2017). The coral concrete exhibits high-early strength or rapid hardening phenomena and the 7 days compressive strength attains 90% of that at 28 days. The brittleness of coral concrete is more evident than that of conventional or lightweight concrete due to the high compressibility and low crushing strength of corals with remarkable intra-granular voids and highly irregular shape (Ma et al, 2019).

There is very limited data available in the literature for mix design of coral aggregate concrete. Only few researchers have provided their trial mixes data as shown in Table 1.

Table 1. Available mix designs in the literature

Reference	Zhou et al. (2018)	Li et al. (2016)	Ma et al. (2019)
Cement	555 kg/m^3	440 kg/m^3	500 kg/m^3
Coral sand	543 kg/m^3	1555 kg/m^3	1300 kg/m^3
Coral Gravel	692 kg/m^3	-	-
Mix Ratio	1: 1: 1.2	1: 3.35: 0	1: 3.35: 0
Concrete Strength	38 MPa	27 MPa	40 MPa
Concrete Density	2095 kg/m^3	2020 kg/m^3	2000 kg/m^3
W/C ratio	0.55	0.59	0.48

Table 1 shows that the cement content should be above 400 kg/m^3 for achieving the strength of 30 MPa or more. It was also reported that better strength and durability was achieved by mixing the coral sand only (with small coral fragments) and by avoiding the coarse coral gravel (Li et al, 2016; Ma et al, 2019). The density of coral concrete for mixes shown in Table 1 was between normal weight and light weight aggregate concrete.

Based on these findings, mix design and properties of coral aggregate concrete consists of coral aggregates sampled from Vanuatu is presented in this paper. Sieve analysis, moisture content and density measurement tests were conducted for the sampled coral sand and gravel. Based on the test data and literature findings a preliminary mix was proportioned to achieve 25MPa concrete strength. The cylinders were tested for the trialed mix and an average strength of 27MPa was achieved. Stress-strain curves, failure mechanisms and elasticity modulus were also determined from the tests. The mix design for other concrete strengths including 32MPa and 40MPa was then similarly designed and is presented in this paper.

2. Tests on coral aggregates

2.1 Density and moisture content of aggregates

The samples of coral sand and gravel from Vanuatu site are shown in Figure 1. Sand sample comprised of coarse sand with small coral fragments as shown in Figure 1(a), while coral aggregates were of irregular shape with a presence of some flaky aggregates as shown in Figure 1(b). Moisture content and bulk densities were determined according to AS1141.5 (2000) for coral fine sand sample and AS1141.4 (2000) was used for coarse coral aggregates. The results are listed in Table 2.

(a) Coral Sand (b) Coral Gravel

Figure 1. Coral sand and gravel samples from Vanuatu

Table 2. Bulk density and moisture content of aggregates

Aggregate type	Density (kg/m^3)	Moisture content
Coral sand	1408	1%
Coral gravel	928	5%

2.2 *Sieve analysis of aggregates*

Particle size grading was carried out for coral sand and gravel using standard procedure following AS1289.3.6.1 (2009). Tables 3 and 4 represents the sieve analysis data for coral sand and gravel sample, respectively.

Table 3. Sieve analysis data for coral sand

Sieve size	Sand retained (gm)	% Retained	Cumulative % Retained	Cumulative % Passing
19	0	0	0.0	100.0
13.2	0	0	0.0	100.0
9.5	1	1	0.6	99.4
4.75	7	4	4.5	95.5
2.36	14	8	12.4	87.6
1.18	39	22	34.5	65.5
0.6	51	29	63.3	36.7
0.425	20	11	74.6	25.4
0.3	14	8	82.5	17.5
0.13	22	12	94.9	5.1
0.075	7	4	98.9	1.1

Table 4. Sieve analysis data for coral gravel

Sieve size	Gravel retained (gm)	% Retained	Cumulative % Retained	Cumulative % Passing
19	110	55.3	55.3	44.7
13.2	45	22.6	77.9	22.1
9.5	36	18.1	96.0	4.0
4.75	2	1.0	97.0	3.0
2.36	0	0.0	97.0	3.0
1.18	0	0.0	97.0	3.0
0.6	0	0.0	97.0	3.0
0.425	1	0.5	97.5	2.5
0.3	1	0.5	98.0	2.0
0.13	1	0.5	98.5	1.5
0.075	1	0.5	99.0	1.0
pan	2	1.0		

Figure 2 shows the grading curve of coral sand. The particle size in coral sand varied from 0.075mm to 5mm and the fineness modulus of coral sand was measured as 4.7 which is higher than the normal sand (2.4-3.5). This shows the presence of coarse particles in the coral sand.

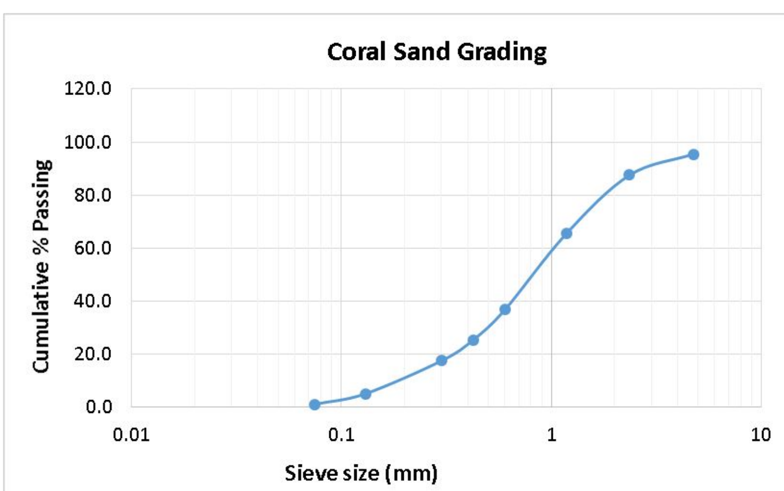

Figure 2. Grading curve of coral sand

The grading of coral gravel in Figure 3 shows that the particle size in coral gravel varied from 5mm to 19mm. The aggregates were also well graded and rough in texture which is advantageous for achieving better bond and strength. However, the porosity of coral aggregate influences the strength and durability of coral concrete greatly and high strength was shown to achieve in the literature by reducing the amount of coral gravel (coarse aggregate) in the mix (Li et al 2016, Ma et al, 2019).

Figure 3. Grading curve of coral gravel

3. Mix design of coral concrete

Mix design was carried out based on the experiment data of aggregates for a trial mix of 25MPa compressive strength. Other required parameters including absorption capacity of coral aggregates, suitable slump and water cement ratio were chosen from the literature. The quantity of coral aggregates was selected somewhere in between what were required for normal weight and light weight concrete. The mix design parameters and calculated contents are given in Table 5.

Table 5. Mix design data

Parameter	Magnitude	Source	Comments
Required strength	25 MPa		
Required slump	100 mm	ACI 211.1-91	Suitable for superstructure
Sp. gravity of cement	3.15	ACI 211.1-91	Ordinary Portland cement
Max aggregate size	19 mm	This paper	
Density of coral gravel	928 kg/m^3	This paper	
Moisture content of coral gravel	5%	This paper	
Absorption capacity of coral gravel	10%	Zhou et al. (2019)	
Density of coral sand	1408 kg/m^3	This paper	
Moisture content of coral sand	1%	This paper	Wetting under light rain
Absorption capacity of coral sand	9%	Zhou et al. (2019)	
Fineness modulus of coral sand	4.7	This paper	Relatively higher than normal sand
Required Water content	205 kg/m^3	ACI 211.1-91	For max aggregate size of 19mm & slump = 100mm
Water/cement (W/C) ratio	0.54	ACI 211.1-91	For 25-30MPa concrete
Air content	2%	ACI 211.1-91	For max aggregate size of 19mm & slump = 100mm
Cement content	380 kg/m^3	Calculated	From water content & W/C ratio
Dry volume of coral gravel	0.35 m^3	ACI 211.1-91 ACI 211.2-91	An intermediate value between normal & lightweight concrete
Volume of coral sand	0.42 m^3	Calculated	By subtracting volume of all other contents from 1m^3 of concrete
Coral gravel content (saturated condition)	357 kg/m^3	Calculated	Using measured density and selected absorption capacity
Coral sand content (saturated condition)	833 kg/m^3	Calculated	Using measured density and selected absorption capacity

The quantities of aggregates (coral sand and gravel) and water were adjusted for the anticipated moisture due to wetting of aggregates. The amount of gravel and sand was increased while water content was decreased to account for measured moisture content in the aggregates tested in the lab.

Final quantities of mix proportions for 25MPa coral concrete are given below:

Cement	:	380 kg/m^3 of concrete
Coral sand	:	840 kg/m^3 of concrete
Coral gravel	:	375 kg/m^3 of concrete
Water	:	179 kg/m^3 of concrete
Coral Concrete Density	:	1775 kg/m^3
W/C ratio	:	0.47

3. Testing of trial mix

A trial mix was undertaken as per the quantities determined in the previous section. The ingredients were mixed, and the slump was tested. Average slump for the mix was measured around 95mm which is close to the designed slump of 100mm mentioned in Table 5. Three (3) standard cylinders of 100mm dia. × 200mm height were poured from the mixed concrete and cured for 28 days. The samples were then testing according to AS1012.9 (2014) under INSTRON compression tester as shown in Figure 4. Displacement control testing at the rate of 1mm/min was used to ascertain the complete stress-strain data. The strains were measured through an extensometer as shown in Figure 4.

Figure 4. Coral concrete cylinder tests

Figure 5 depicts the failure mechanism of coral concrete under uniform compressive load. A columnar failure was observed with plane of failure passing through the coral aggregates instead of interfacial zone between the cement matrix and aggregates which is common in the conventional concrete. This type of failure mechanism is a consequence of porosity and lower density of coral aggregates, similar observations were made in Ma et al. (2019). Table 6 lists the density, failure load and compressive strength of tested cylinders. The results were very consistent with a lower coefficient of variation which shows the uniformity of mix. The average density of coral concrete was 1980kg/m3 which is slightly higher than expected, while the mean compressive strength was determined as 27MPa which is close to the designed mix strength of 25MPa.

Figure 5. Failure mode of coral concrete under compression

Table 6: Density and strength of coral concrete

Sample Number	Weight (kg)	Density (kg/m^3)	Load (kN)	Strength (MPa)
1	2.96	1885	220	28.0
2	3.16	2012	200	25.5
3	3.21	2044	204	26.0
Mean		1980	208	27.0
Coefficient of Variation (CoV)		4%	5%	5%

Stress-strain curves of the tested cylinders are exhibited in Figure 6. The peak strain for all specimens was measured around 0.002mm/mm and an average failure strain was 0.00225mm/mm which shows a brittle post peak response. Again, this response verifies the failure due to quicker cracking of porous coral aggregate once the failure commences as shown in the failure mode in Figure 5. The elastic modulus of coral concrete was calculated through the slope of elastic curve and an average of 13,000MPa was obtained for 25MPa concrete mix which is also lower than normal weight concrete of the same strength.

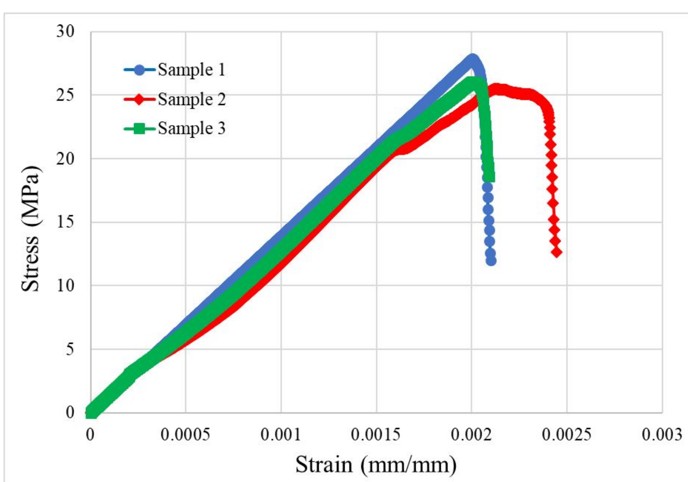

Figure 6. Stress-strain curves of the coral concrete in compression

4. Mix design for different strengths

Design procedure similar to what was explained in the previous section for 25MPa, using the coral sand and gravel properties shown in Table 5, was then employed to compute the mix design proportions for 32MPa and 40MPa coral concrete strengths. The proposed mix quantities are shown in Table 7.

Table 7. Mix design for different coral concrete strengths

Quantities	25MPa	32MPa	40MPa
Cement	380 kg/m^3	440 kg/m^3	500 kg/m^3
Coral sand	840 kg/m^3	805 kg/m^3	770 kg/m^3
Coral Gravel	375 kg/m^3	375 kg/m^3	375 kg/m^3
Mix Ratio	1: 2: 1	1: 1.8: 0.9	1: 1.6: 0.8
Concrete Density	1775 kg/m^3	1795 kg/m^3	1815 kg/m^3
W/C ratio	0.47	0.41	0.37

The mix proportions presented in Table 7 were designed for 100mm slump. Water cement ratio was reduced, and cement content was increased gradually from 25MPa to 32MPa and 40MPa strengths as shown in the Table 7. It is suggested that in order to control the workability of mix with lower water cement ratio, plasticizer should be added for ease of pouring and placement.

5. Conclusions

This paper presents mix design and properties of coral aggregate concrete specifically for the Oceania islands. The coral aggregates were sampled from Vanuatu island and preliminary tests were conducted to ascertain the densities, moisture content and grading of aggregates. This data was then used to carry out a trial mix design for 25MPa strength. The water and cement content in the trial mix of coral concrete were chosen similar to the requirement of normal weight concrete. The mix proportions were trialed, and cylindrical specimens were prepared and tested after 28 days of curing. Stress-strain curves, compressive strength, density and elastic modulus for the designed coral concrete mix were measured. The mix design was then similarly carried out for 32MPa and 40MPa strengths. Following are the main conclusions from the study:

- The volume of coarse aggregate in all the mixes was selected based on the fineness modulus of sand of 4.7 from the test results, which implies to coarseness in the sand sample and hence a reduced volume of coarse aggregates in the mixes was employed to increase the strength and density of coral concrete.
- The density of coral aggregate concrete was determined in between the light weight and normal weight concrete. The average density was determined as 1980 kg/m3.
- Failure of the samples occurred because of the cracking through the coarse coral aggregates amid their porosity and lower density in comparison to normal weight concrete where the failure is dominated in the interfacial zone between the aggregates and the cement matrix.
- The post peak response of coral concrete was observed brittle due to cracking of the coral aggregates.
- The modulus of elasticity and failure strain of coral concrete was also observed lower than the normal weight concrete due to porous nature and crushing of coral aggregates.

6. Acknowledgement

The author would like to acknowledge the samples of aggregates provided by Tim Benneton Architects, Brisbane and financial support of Bligh Tanner, Brisbane to conduct this research.

7. References

1. American Concrete Institute (ACI) Committee 211.1-91, Standard practice for selecting proportions for normal, heavyweight and mass concrete, Part 1, ACI Manual of Concrete Practice, 1994.
2. American Concrete Institute (ACI) Committee 211.2-91, Standard practice for selecting proportions for structural lightweight concrete, Part 1, ACI Manual of Concrete Practice, 1994.

3. AS 1141.4-2000 (R2013). Methods for sampling and testing aggregates Bulk density of aggregate Standards Australia, 2013.
4. AS 1141.5-2000 (R2016). Methods for sampling and testing aggregates Particle density and water absorption of fine aggregate, Standards Australia, 2016.
5. AS 1289.3.6.1-2009. Methods of testing soils for engineering purposes Soil classification tests - Determination of the particle size distribution of a soil - Standard method of analysis by sieving, Standards Australia, 2009.
6. Huang Y, He X, Sun H, Sun Y, Wang Q. (2018). Effects of coral recycled and natural coarse aggregates on the mechanical properties of concrete. Construction and Building Materials 192: 330–347.
7. Li WF, Guan J, Ma SH, et al (2016). Application of sea sand and coral reefs in the production of concrete mixed with seawater. Concrete 5: 148–152.
8. Liu J, Ou Z, Peng W, Guo T, Deng W and Chen Y. (2018). Literature Review of Coral Concrete. Arabian Journal of Science and Engineering 43:1529–1541.
9. Ma L, Li Z, Liu J, Duan L, and Wua J. (2019). Mechanical properties of coral concrete subjected to uniaxial dynamic compression. Construction and Building Materials 199: 244–255.
10. Wang A, Lyu B, Zhang Z, Liu K, Xu H and Sun D. (2018). The development of coral concretes and their upgrading technologies: A critical review. Construction and Building Materials 187: 1004–1019
11. Wang X, Yu R, Shui Z, Song Q, Zhang Z. (2017). Mix design and characteristics evaluation of an eco-friendly Ultra-High-Performance Concrete incorporating recycled coral based materials. Journal of Cleaner Production 165:70-80.
12. Wang Y, Zhang S, Niu D, Su L and Luo D (2019). Effects of silica fume and blast furnace slag on the mechanical properties and chloride ion distribution of coral aggregate concrete. Construction and Building Materials 214: 648–658.
13. Wu W, Wang R, Zhu C and Meng Q (2018). The effect of fly ash and silica fume on mechanical properties and durability of coral aggregate concrete. Construction and Building Materials 185: 69–78.
14. Zhou W, Zhou Y, Feng P, Wang Z, Wang J, and Song P. (2019). Mechanical and Durability Properties of Coral Aggregate Concrete. American Concrete Institute, ACI special edition SP330: 175-188.