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THE EFFECTS OF ADJUSTING AGGREGATE FINENESS AND MIX PROPORTIONS TO PRODUCE CONCRETE MASONRY BLOCKS OF VARIOUS STRENGTHS

Bown, Katherine[1,2], Talukdar, Sudip[1], Svetlana Brzev[1], Nguyen, Brandon[1], Zhang, Chi[1], Booth, James[1] and Cox, Neil[1].
[1] British Columbia Institute of Technology, Canada
[2] kbown2@my.bcit.ca

ABSTRACT

In the winter of 2010, over 200,000 people lost their lives in the Haiti earthquake. Many of the structural failures, and the associated loss of life can be attributed to the use of low strength masonry blocks. Many countries rely on masonry as an economical building material. But these same regions do not have access to the level of standards and testing equipment available that countries such as Canada and USA have. The 2010 Haiti earthquake was the motivation behind a British Columbia Institute of Technology (BCIT) research project for a low-cost, easy-to-use, non-destructive testing (NDT) device for masonry blocks.

While working on this project, it was noted that there is limited research for weak masonry. To proceed with testing the prototype device, there was a need to mimic real-life masonry for our testing procedures. Further many of the code equations currently used are based on assumptions associated with the mechanical behavior of normal strength, or strong concrete, and the empirical equations provided in Canadian codes do not work well for the weaker target material.

The motivation for creating mix designs for weak concrete was to test a large sample set of specimens over the range of strengths expected to be encountered in the field with sub-standard construction practices. Furthermore, by having specimens in the lower strength ranges, it gives the opportunity to study the effectiveness of the various code equations on materials of sub-Canadian standards.

This paper outlines the procedures we used to create repeatable mix design for weak concrete, and review the results of our experiments on a range of concrete strengths. Various mix designs were tested. Mixes varied the amount, gradation and type of aggregates, cementitious content, and water content. It was found that the strength range was directly correlated to the shape of the gradation curve for the fine aggregate. By varying the amount of fine aggregate in the mix, and adjusting the fineness of the aggregate used, mixes of varying strength could be repeatedly produced. Using the data from testing these mixes, new equations are being developed to define material behavior with a particular focus on the acoustic response of lower strength mixes.

Keywords: concrete, masonry, design, NDT, code, aggregate

1. INTRODUCTION + BACKGROUND

Hundreds of thousands of lives have been lost to seismic events. Many of these deaths could have been prevented if there had been effective and economical ways to test the strength of the masonry units used throughout the world as a "modern" construction material. In Canada, we have strict building codes and advanced quality control/ testing methods readily available. Unfortunately, in many developing countries, due to a lack of resources, quality control is often lacking in construction practices.

Figure 1 illustrates the testing method for concrete masonry blocks recommended for the rebuilding in Haiti after the 2010 earthquake. The general idea is that if 5 random blocks can withstand being dropped from 1.5 m onto hard soil, then the batch will have sufficient strength.

Clearly, there is a need to develop a, low-cost, easy to use, non destructive testing (NDT) device that could be used in all regions of the world. The idea has been developed at the British Columbia Institute of Technology (BCIT). The final prototype of the testing equipment involves: a striker to strike the block surface and make the sound (excite the specimen); a cellphone to record the sound (resonant frequencies); and an app to determine the strength (apply empirical function to determine strength). The other inputs for the app will include the geometry of the specimen, location of test, and material type.

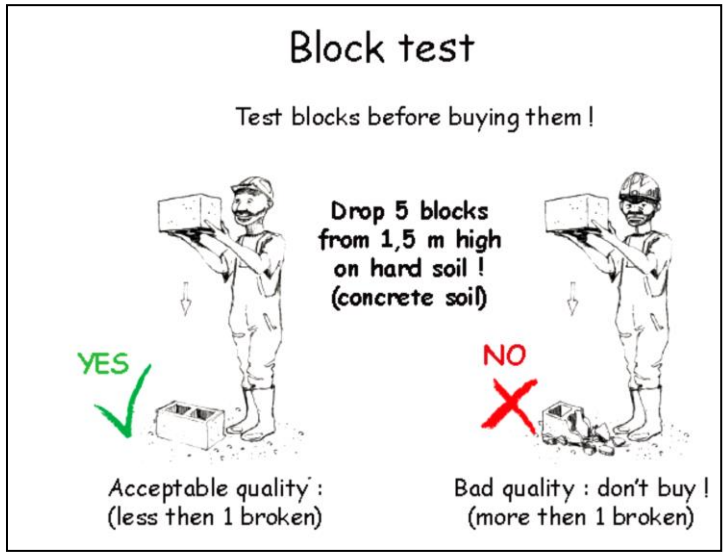

Figure 1: Drop Test (Swiss Development Corporation, accessed 2015)

To develop a reliable relationship between the concrete strength and frequency, ideally test specimens should have been prepared that would be similar in strength to actual blocks that would be put in service. This meant working outside of the strength ranges that are used in Canada and other developed countries. In Canada, the minimum strength limit for masonry blocks is a compressive strength (F_c') of 15MPa. In other countries, the standard is 10MPa, but most blocks used in construction are often 5MPa or less. Therefore, our testing included specimens ranging from below 5MPa.

The three basic components of concrete are cement, aggregates and water. The aggregates can then be further divided into coarse (gravel) and fine (sand). In Canada, CSA provides standards for the coarse and fine aggregates and allowable ratios for the aggregates and the cement to aggregate ratio (CSA, 2011). Some countries use only sand in their concrete mixes. Finally, many regions have no standards for cement to aggregate ratios and only guidelines for aggregate quality, or the standards are not implemented or enforced.

Initially, it was assumed that making concrete less than 10MPa in strength would be simple. Research students would just follow simple mixing procedures that used less cement and allow the specimen to air dry instead of being cured properly. Unfortunately, this system could not consistently produce concrete less than 10MPa and not less than 5MPa. Clearly, the type, proportion, and gradation of aggregates used has a huge effect producing lower strength concrete.

Chane et al (2013) initially looked into the effects of aggregate ratios, curing conditions, and consolidation methods on concrete strength for test blocks. However, they were not able to reliable produce concrete of strengths less then 10MPa. McKeeny (2008) looked into the composition of blocks used in Haiti, and found that unless washed properly, the fine aggregate used there produces poor quality concrete. From her research it was further apparent that the quality of sand plays an important roll in the quality and strength of concrete.

2. METHODOLOGY

Building upon the findings of McKeeny (2008), it was decided to use "poor" quality sand for the concrete mixes. Unwashed bench (river) sand was chosen because it had a fine texture, had high levels of microfines along with organic impurities. Discussions regarding compaction and mixing procedures resulting in an agreement to duplicate concrete batching similar to methods found in developing countries.

The first step was to create mix designs. Two sets of mix designs were created: the first to refine the mixes (Set A), the second to mass produce companion blocks and cylinders (Set B). After reviewing the previous student research and background material, we chose ambient curing conditions with no extra moisture added and compaction method of consolidation. This most closely matched typical conditions in field.

For Set A two types of coarse aggregate were tested. Standard 19mm angular granite course aggregate was tested, along with12.7 mm pea gravel. Pea gravel was tested as similar round river rock is often used in developing countries. The gradation chart for each type of coarse aggregate is provided in Table 1/Figure 2:

Table 1: Coarse Aggregate Gradation

Type	**Pea gravel**	**Lab Aggregate**
Size	% Retained	
19 mm	0.0%	4.7%
12.7 mm	45.6%	77.0%
9.5 mm	51.5%	15.8%
4.76 mm	2.6%	1.0%
Maximum Size	12.7 mm	19 mm
Specific Bulk Density	2.69	2.68

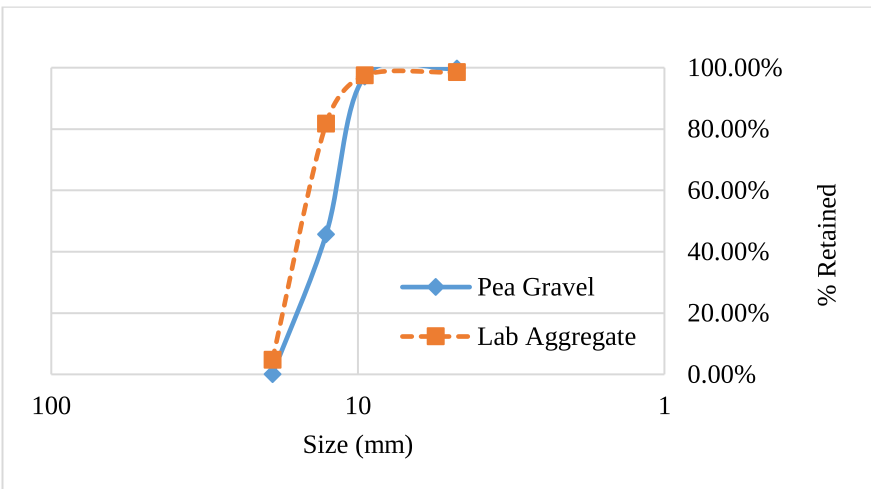

Figure 2: Coarse Aggregate Gradation Curve

In addition, two types of sand were tested. One was sand taken from the Fraser River, the second type was a common laboratory sand. Gradation charts for each type of fine aggregate are provided in Table 2/Figure 3.

Table 2: Set A Fine Aggregate Gradation

Type	Standard Lab	Unwashed River A
Size	% Retained	
4.75 mm	0.66%	0.53%
2.36 mm	8.94%	0.66%
1.18 mm	18.81%	0.90%
600 µm	22.63%	10.67%
300 µm	25.22%	53.43%
150 µm	16.51%	20.99%
750 µm	4.83%	6.45%
% passing #200	2.55%	6.56%

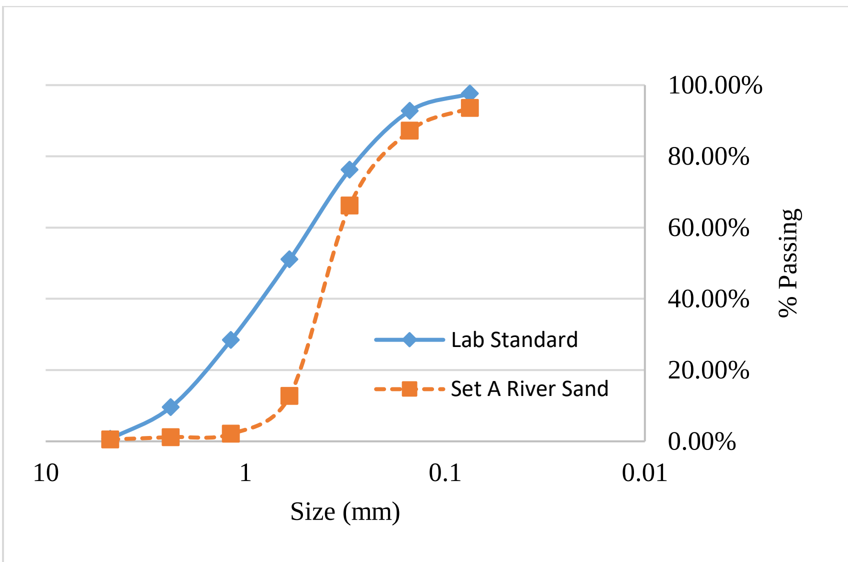

Figure 3: Fine Aggregate Gradation Curve

Table 3 summarizes the initial mixes tested:

Table 3: Initial Mixes

Mix	Fine Aggregate	Coarse Aggregate	w/c
A1	River	19 mm	0.65
A2	River	12.7 mm	0.65
A3	River	No	0.65
A4	River	19 mm	0.75
A5	River	12.7 mm	0.75
A6	River	No	0.75
A7	River	19 mm	0.85
A8	River	12.7 mm	0.85
A9	River	No	0.85
A10	Laboratory	19 mm	0.65
A11	Laboratory	12.7 mm	0.65
A12	Laboratory	No	0.65
A13	Laboratory	19 mm	0.75
A14	Laboratory	12.7 mm	0.75
A15	Laboratory	No	0.75
A16	Laboratory	19 mm	0.85
A17	Laboratory	12.7 mm	0.85
A18	Laboratory	No	0.85

Mixes A1-A3 were found to be too dry, and Mixes A16-A18 were found to be too wet. Originally, a binder: aggregate of 1:4 was to be used for all mixes. However, it was found for the mixes without any coarse aggregate, additional binder was required to coat the aggregate surfaces. Therefore, a ratio of 1:3 was used for all sand only (Mixes A3, A6, A9, A12, A15, A18) and the 1:4 was used for the sand + coarse mixes (Mixes A1, A2, A4, A5, A7, A8, A10, A11, A13, A14, A16, A17).

A number of cylinders were batched for each of the different mixes, to be tested at 7,14,21 and 28 days. Based on the results of the compressive tests, it was found that the coarse aggregate type had minimal effect on the low strength mixes. On the other hand, the fine aggregates had a very significant effect on the strength. Therefore, for the second phase of testing (Set B), only 12.7 mm coarse aggregate was used, combined with various fractions of river sand and laboratory sand. For Set B, the different mixes are summarized in Table 4:

Table 4: Second Concrete Design Matrix

Mix	River Sand: Total Aggregate (mass)	Laboratory Sand : Total Aggregate (Mass)	Coarse Aggregate : Total Aggregate (mass)	w/c
B1	0.18	0.42	0.4	0.7
B2	0.3	0.7	0	0.75
B3	0.7	0.3	0	0.78
B4	0.5	0.5	0	0.8
B5	0.3	0.3	0.4	0.8

B6	0.5	0.5	0	0.85
B7	0.3	0.3	0.4	0.85
B8	0.42	0.18	0.4	0.85

For all the different mixes, cylinders were batched, prepared and tested as per CSA 23.2 (CSA, 2011).

Once the specimens were ready, a set of physical non-destructive tests were completed before the specimen was subject to its compressive test. Tests include:

1. Geometry and mass
2. Acoustic tests
3. Ultrasonic Pulse Velocity
4. Modulus of Elasticity
5. Compressive Strength

The remainder of this paper focuses on the relationship between compressive strength and aggregates.

3. RESULTS

Aggregates tests included sieve analysis for both coarse and fine, and regular moisture content used for adjusting water requirements for maintaining water/cement ratios.

It was observed that the failure mode for the weak cylinders was in the binder/paste of the concrete, not through the coarse aggregate. Therefore, the coarse particle type did not affect the strength of the weaker mixes. However, it had a moderate effect on the stronger mixes (Figure 4).

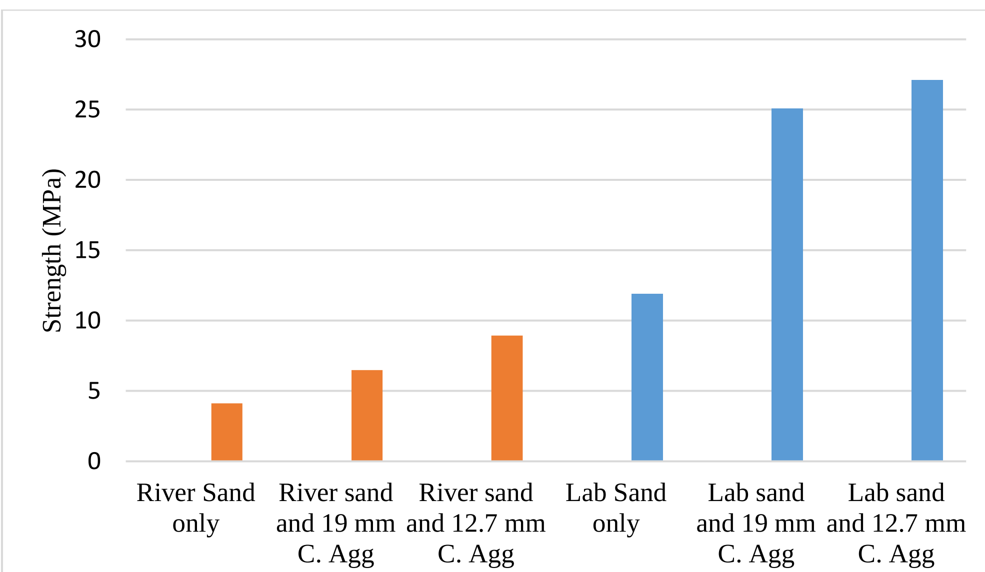

Figure 4: Compressive Strength for Set A by Aggregate Type

It was noticed that the unwashed river sands used in Sets A and B had a higher percentage of particles passing the #200 sieve. In fact, when plotting the gradation curves for these sands, it was noticed that they both fell outside the acceptable CSA grading criteria (Figure 5).

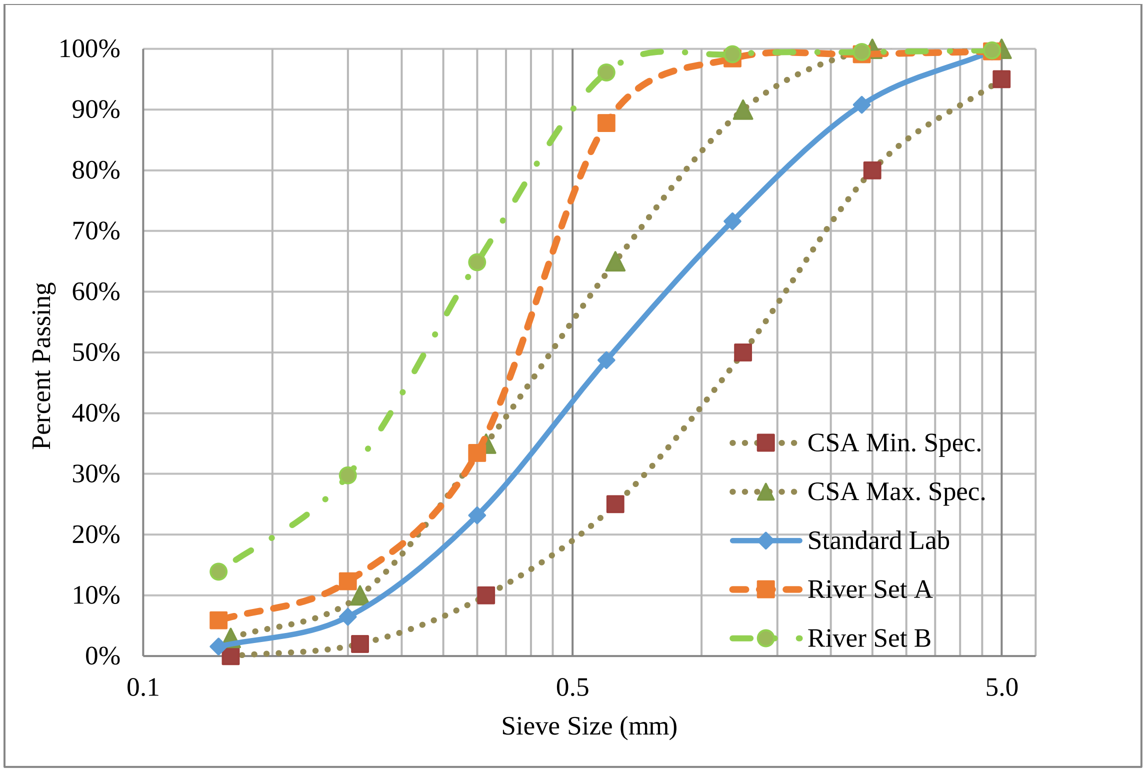

Figure 5: Fine Aggregate Gradation Curves

The particles passing the #200 sieve are silts and clays (microfines), which are consider detrimental for concrete mixes, as they disrupt the cement paste-aggregate bond.

The percent passing the #200 sieve and the fineness modulus was also compared (Table 5).

Table 5: Fineness Modulus and Percent Passing 200 for Fine Aggregates

Bulk Sand Type/ Blended Sand Type	**Fineness**		**Percent Passing 200**	
	Average	**SD**	**Average**	**SD**
Standard Lab	2.59	0.01	2.6%	1.1%
Set A: River	1.70	0.02	6.6%	0.5%
Set B: River	1.11	0.004	14.3%	0.3%
Blend 1 - 50R-50S	1.97	0.01	8.8%	0.2%
Blend 2 - 30R-70S	2.13	0.12	6.0%	0.2%
Blend 3 - 70R-30S	1.59	0.02	10.8%	0.6%

The fineness modulus is a measure of the distribution of particles. The lab sand had a fineness modulus of 2.59 and the % passing 200 was 2.6%. The CSA limits for these are between 2.3 and 3.1 for fineness modulus and less than 3% passing 200. The river sands used in Sets A and B were outside of the CSA limits. Because the River sands contained such a high percentage of microfines, sand blends were used in Set B combining fractions of river sand and laboratory sand, so that the blocks cast would cast and develop some strength. Mixes B4, B6, B5 and B7 used a 50:50 mix of river and lab sand respectively, Mixes B1 and B2 used a 30:70 mix of river and lab sand, while Mixes B3 and B8 used a 70:30 mix of river and lab sand (Table 4).

The lower the value of fineness modulus, the higher the % passing the #200 sieve in a mix. There was clearly a correlation between lower values of FM and lower strength (Figure 6, Figure 7). The second factor influencing strength is well known; the lower the w/c ratio used, the higher the strength of the mix (Figure 8).

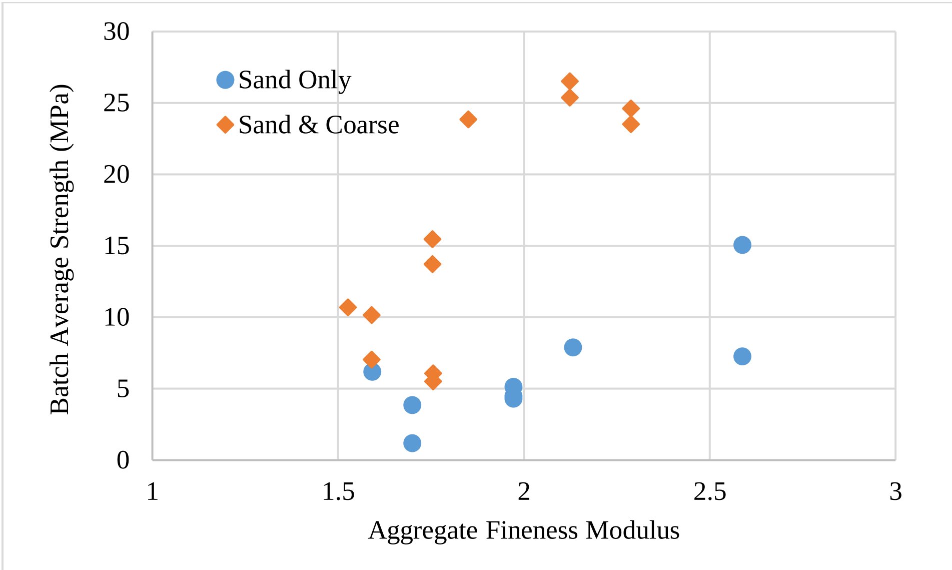

Figure 6: Strength vs Fineness Modulus

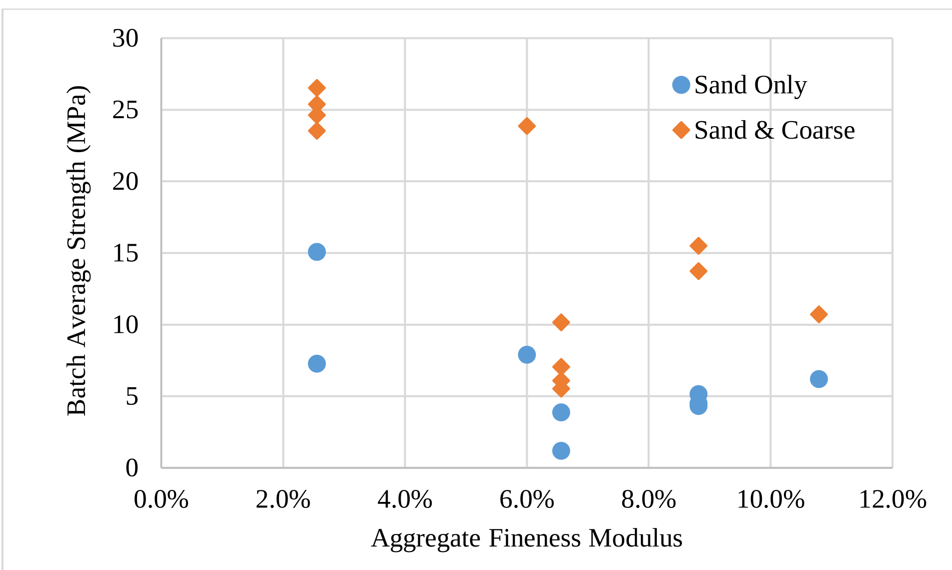

Figure 7: Strength vs % Passing #200 (all water contents)

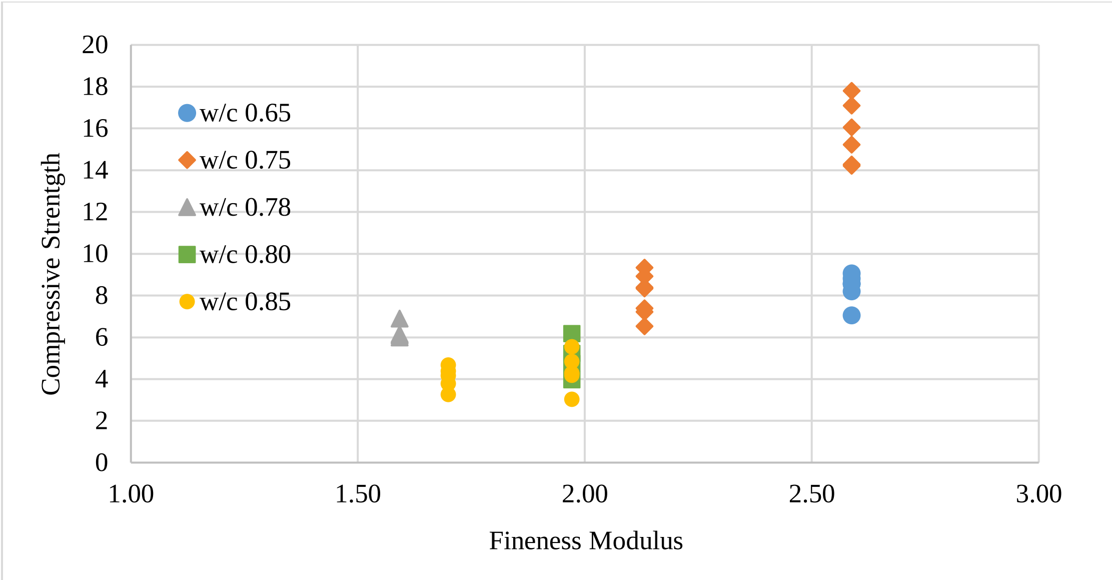

Figure 8: Effect of w/c on Compressive Strength

Modulus of elasticity was recorded on a select set of cylinders (ASTM, 2002). The experimental value was compared to code equations (CSA, 2014), (ACI, 2011), (Neville, 2011) as well as our theoretical value based on cylinder frequencies (Booth, 2017) and plotted against each other. The formula for the theoretical frequency value is based on Rayleigh's work on acoustic behaviour of a solid. The following graph plots the residuals for the predicted modulus of elasticity values from the code and the frequency. The predicted CSA and ACI values have a systematic increase with increasing elastic modulus. The deviation from observed values for the modulus are significant less than predicted values once the strength and modulus become smaller when the theoretical formula is applied (Figure 9).

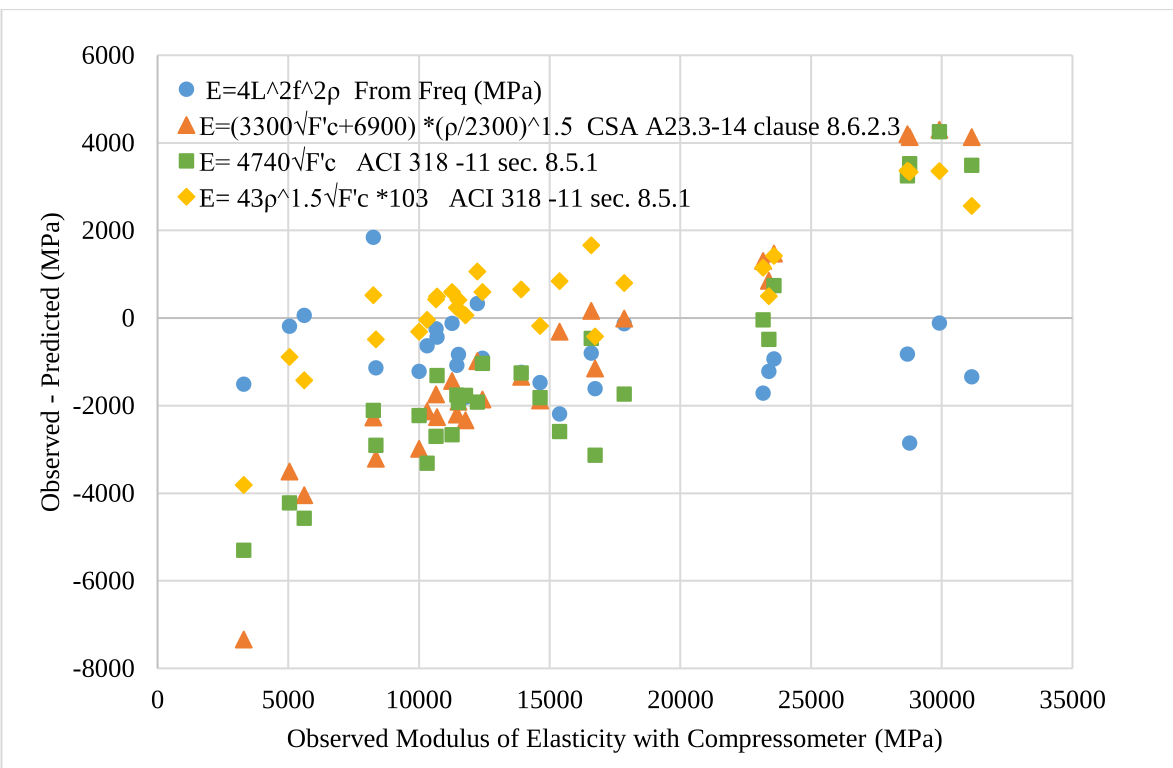

Figure 9: Code Equations vs Measure Modulus of Elasticity

4. SUMMARY AND CONCLUSIONS

The results from this research illustrate the impact of sand on concrete quality. The assertion by McKeeney (2008) was confirmed. To produce masonry blocks of good quality, fine aggregates must be washed, and not contain excessive amounts of microfines passing the #200 sieve. Mixes should contain coarse aggregate, and not be fine aggregate only mixes. This should be emphasized when constructing masonry units, or concrete mixes in areas where quality control may be substandard. Furthermore, the relevant code equations in CSA and ACI to calculate elastic modulus are not suitable for lower strength concrete. Therefore, new equations need to be developed and applied when looking at a wide range of strengths.

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