Compressive Performance of Recycled Aggregate Mortar

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Abstract

The use of recycled materials in construction is gaining popularity in efforts to attain net-zero status for commercial construction. When investigating the applicability of new materials in building construction it is prudent to first insure that the material used in replacement equals the strength performance of the natural material being replaced. For concrete masonry systems, the compressive strength of the system, f'_m is used to describe strength performance.

The study uses the prism test method to compare the f'_m of prisms made with standard normal weight masonry sand to the f'_m of prisms made with recycled materials including crushed demolition rubble and brick manufacturing waste. Several mix designs have been tested for each of the recycled aggregates used to determine optimum mix ratios. The crushed demolition rubble is comprised of crushed brick and mortar while the brick manufacturing waste is solely made up of crushed brick. A sieve analysis for each of the materials is conducted for each of the materials in order to better understand how the distribution of the aggregate sizes affects the overall strength of the mortar.

The effects of workability and bonding with relation to water content for each of these mixes have also been explored. Alternatives to ASTM C109 for finding accurate mortar strength values using the same mortar from the prism tests are considered. In the case of the crushed demolition rubble and the brick manufacturing waste, the elongation of the aggregates and how they affect the height of the mortar joint is addressed.

Compression prism and two-inch cube data for each of the recycled materials will be analyzed in the paper and compared to standard normal weight masonry sand.

Introduction

As recycled materials continue to gain popularity in the construction industry, it is important to attempt to incorporate these materials in different aspects of construction. As with any new building material, exhaustive testing is needed to ensure its operating parameters meet the current standard. This study focuses on the compression performance of mortar consisting of recycled aggregates in place of natural aggregates.

The concept of using recycled aggregates in concrete has grown in popularity while conversely, the mainstream masonry building community has failed to capitalize. As the cost of "new" aggregates rise, the need for alternative aggregates of comparable or greater quality will be paramount. The current practice of landfilling demolition rubble is not a sustainable practice as the amount of landfill space is finite. Overall, the ability to recycle and reuse these materials will serve to reduce the amount of material that needs to be quarried while also reducing the amount of material that needs to be disposed of.

The materials that will be tested in this study include two types of recycled crushed red clay brick. The first is demolition rubble that includes crushed brick and crushed masonry mortar. The second is brick manufacturing waste that is made up of pure crushed brick. These materials would have been used for none construction purposes or put into a landfill.

A net-zero building is one that produces at least as much energy during its lifetime as it consumes in construction and service life. Finding more ways to utilize recycled materials in construction can greatly reduce the energy that goes into finding new materials while simultaneously cutting costs.

One of the common issues that occur during research with recycled aggregates is the difference in water absorption. Recycled aggregates that are made with brick or other fired clay materials, which were used in this study, have higher moisture absorption than typical normal weight aggregates [1]. This means that more water needs to be added to the mix in order to achieve the same workability and flow, which has negative impact to the final strength of the concrete masonry specimens [2].

The use of these materials in concrete has been extensively studied, [1, 2, 3, 4, 8], with varied results. Some sources of variation in the data retrieved could be credited to inconsistencies in the source materials or differences in testing procedures. Etxeberria et al. (2007) reported that concrete that is made with no more than 25% recycle concrete aggregates could be used in structural applications, while higher percentages had an unacceptable reduction in strength compared to the control [3]. A second study using recycled concrete aggregate from a demolished airport also found that as the percentage of recycled aggregates is increased, the strength of the resulting concrete specimens is decreased [4].

While research on the use of recycled aggregates in concrete is fairly abundant, the use of recycled materials in masonry mortar is less common. Masonry mortars that include atypical materials ranging from high impact polystyrene [5] to recycled glass and metakaolin [6] have been researched. In mortar or concrete, bonding between the cement paste and the aggregates used is dependent on variables including aggregate angularity and water absorptivity. This presents a possible challenge when using atypical materials as aggregates due to the differences in shape and water retention compared to natural aggregates. If this bond strength is not achieved, slippage between the aggregate particles could cause a decrease in the compressive strength of the mortar, although in some cases an adequate bond is made between the "new" material and the cement paste due to an acceptable aggregate surface roughness [7].

Prism testing, constructed according to ASTM C1314 [9], will be used to test and compare the compressive strength of the mortar as part of a concrete masonry building system. Any variability in the concrete masonry units used will result in a corresponding variability in the prism tests. For this reason prism, compression tests will be used primarily to verify that the performances of the recycled aggregate mixes under compression are comparable to the ASTM standard C-144 sand mix [10].

Mix Design and Preparation

A mix design of three parts aggregate to one part cement by volume was employed for use in each of the test series. This falls in the middle of the acceptable range of values for aggregate ratio as per ASTM C270-12 [11]. This is due to balancing the strength of the mortar with the cost to produce. As the cement is the most expensive part of the mortar mix, it is preferred to use the least amount possible while still maintaining the necessary strength of the material.

Any time a material is used in a different application, there will be challenges to overcome, and this study was no exception. Over the course of testing, the mortar mixes utilizing crushed brick recycled aggregates provided unique challenges not present in mortar mixes that employ sand. These challenges include bonding issues, joint height, particle elongation, particle angularity, and water content. The test methods used were improved to overcome these challenges and gave a more in depth understanding of the behavior of the recycled materials being used.

Certain particles contained in the recycled demolition brick sand and the brick manufacturing waste have the tendency to be elongated and angular as shown in Figure 1. This does not allow prisms to be constructed with a 3/8" mortar joint so these particles were sieved out using #4 and #8 sieves. Preliminary cube testing indicated that including these long, angular particles in the mortar sample yielded specimens that had a higher compressive strength than those that were made with these particles removed.

Figure 1. Elongated and angular particles

In order to prevent premature local failures of the prism specimen due to surface irregularities, it is necessary to provide a uniform bearing area to aid in even load distribution. This process is referred to as "capping the specimen." The material used for capping the prism test series is a sulfur cement capping compound provided by ASTM C1552-12 [12]. A capped specimen is illustrated in Figure 2.

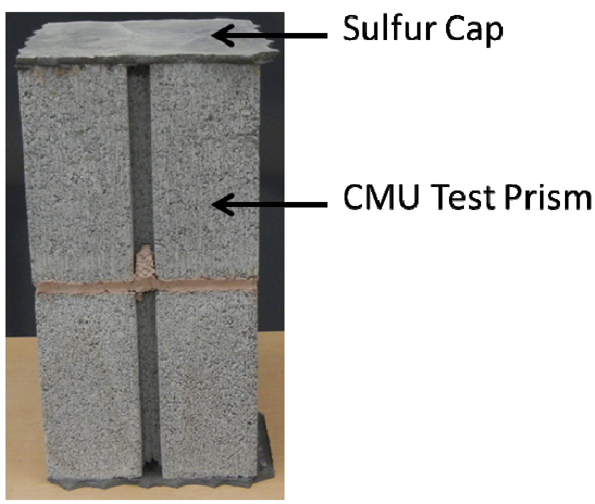

Figure 2. Illustration of capped prism specimen

The effect that water content has on the behavior of masonry mortar is extremely important as it affects nearly every aspect of the mortar's characteristics including workability and bonding to the final compressive strength. To achieve the necessary workability, the mason was given the freedom to dictate the amount of water added to the mix in real time, while the final amount of water added was recorded. Flow tests were performed on a flow table as per ASTM C1437-13 [13] at 1 minute after mixing and 30 minutes after mixing. The mortar sample that was used to create the masonry prisms was the same that was used to create the mortar cubes.

Table 1. Flow rates for the aggregates tested

Aggregate	@ 1 minute	@ 30 minutes
C-144 Masonry Sand	190	190
Demolition Brick Sand	172	165
Brick Manufacturing Waste	165	159

The prisms that were tested utilized lightweight concrete masonry units that have a higher absorption rate than normal weight concrete masonry units. This affected the mortar that was used to build the prisms by drawing more water out of the mortar than a normal weight concrete masonry unit would.

Cube Testing

The standard 2" masonry mortar cube test as described in ASTM C109 [14] sets a clear guide for creating and testing 2" mortar cubes that utilize typical aggregates. However, the aggregates tested in this study were not typical and therefore have different water absorption qualities. Since the brass that makes up the molds used in ASTM C109 [14] will not absorb any water from the specimens they contain, the water content of the sample is accordingly reduced to account for this effect by slowly adding water to the mix and testing the flow as per ASTM C1437-13 [12].

ASTM C109 [14] specifies the water content of the sample prior to being inserted into the brass molds must produce a flow of 110 ± 5 in 25 drops of the flow table. This results in a very dry state for the mortar and in the case of the materials tested with the exception of sand, makes it very difficult to obtain a clean, uniform cube. Therefore, an alternative method for creating companion cubes was explored. One of the requirements for the alternative test was that the same mortar sample that was used to create the masonry system prisms could also be used to create the mortar companion cubes; thereby making the companion cubes a more accurate measure of the mortar in the system prisms.

This alternative method is similar to the method for making 4" x 8" grout prisms outlined in ASTM C1019-13 [15]. The masonry units were positioned such that the opening measured 2" x 2". The faces of the lightweight concrete masonry units used in construction of the molds were first lined with a thin permeable material to prevent the mortar from adhering to the unit and the bottom of the mold was lined with an impermeable material to prevent moisture loss not experienced in-situ. After 24 hours in the molds, the specimens were removed from the molds and placed in a lime bath to cure for 28 days. On day 28, the specimens were removed and cut into three 2" high cubes on a lapidary slab saw before being tested. The goal of this method of making mortar cubes is to more accurately mimic what would be occurring in the field. All specimens of each type of mortar mix were tested within 10 minutes of each other to attempt to eliminate any variability in moisture content between the specimens.

Table 2. Alternative cube results

	Ultimate Strength (PSI)		
Cube #	**Masonry Sand**	**Demo. Brick Sand**	**Brick Manuf. Waste**
1	1122	2480	2193
2	1047	2886	2102
3	1335	2775	2535
4	1815	2459	1856
5	1732	2133	2109
6	2074	2683	1743
Average	1521	2569	2090

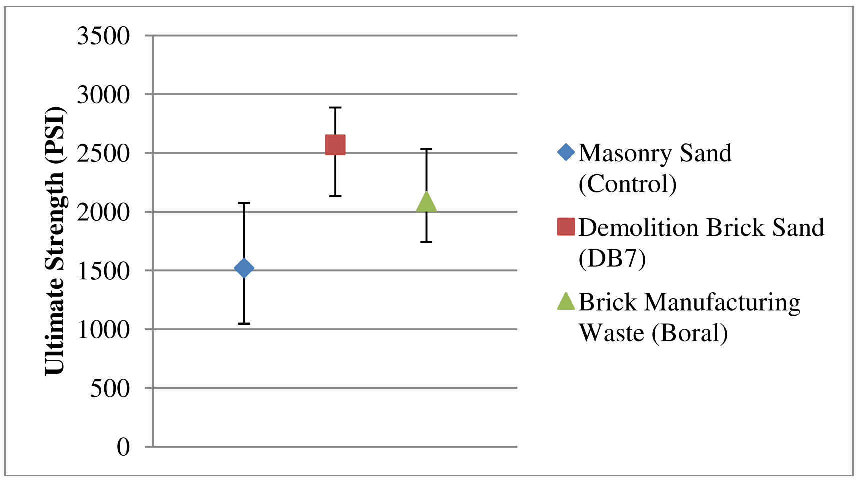

Figure 3. Alternative cube results

The results shown in Table 2 and Figure 3 indicate that the mortars made with the recycled brick aggregates are generally stronger than the C-144 masonry sand that was used as the control with the demolition brick sand being 169 % stronger and the brick manufacturing waste being 137 % stronger. From this data, it was expected that this trend would be reflected in the results for the prism testing.

Prism Testing

Prisms were constructed according to ASTM 1314-12 [9] and tested after 28 days of curing in a lime-water bath. Only 28 day testing was required due to the goal of this testing being the validation of the recycled materials in question. Within 24 hours prior to testing, the prisms are removed from their airtight bags and capped.

Table 3. Prism compression results

	Ultimate Strength (PSI and MPa)					
Prism #	**Masonry Sand**		**Demo. Brick Sand**		**Brick Manuf. Waste**	
	PSI	**MPa**	**PSI**	**MPa**	**PSI**	**MPa**
1	1864	12.85	1257	8.67	1104	7.61
2	1182	8.15	1525	10.51	992	6.84
3	887	6.12	2124	14.64	1020	7.03
4	2284	15.75	946	6.52	992	6.84
5	1010	6.96	1192	8.22	1142	7.87
6	1179	8.13	1552	10.70	1671	11.52
7	1646	11.35	1732	11.94	1125	7.76
8	1344	9.27	1380	9.51	1071	7.38
9	1552	10.70	1270	8.76	1299	8.96
10	895	6.17	1596	11.00	1116	7.69
Average	1384	9.54	1457	10.05	1153	7.95

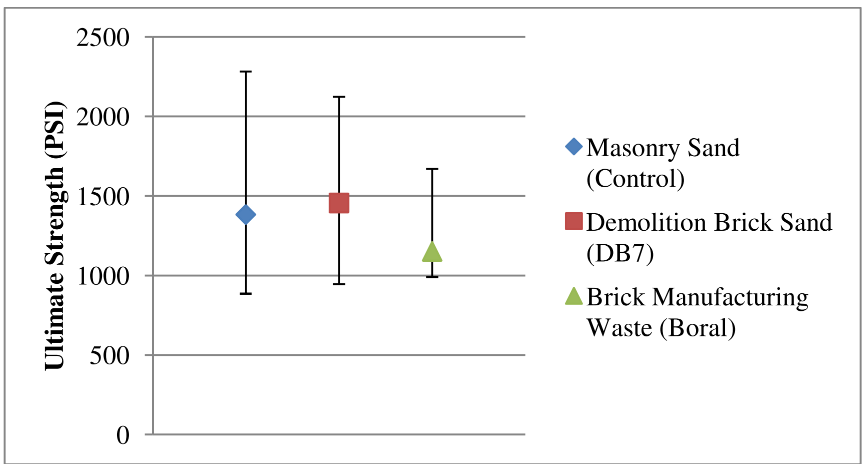

Figure 4. Prism compression results

These results indicate that the demolition brick sand exhibits 105% of the current standard's compressive strength performance. Meanwhile the brick manufacturing waste exhibits only 83% of the masonry sand's compressive strength. This could be due to the differences in makeup between these materials. The demolition brick sand is made up of crushed brick and mortar, while the brick manufacturing waste is made up of only crushed brick. The presence of mortar cement particles in the demolition brick sand could have been the reason for the increased compressive strength.

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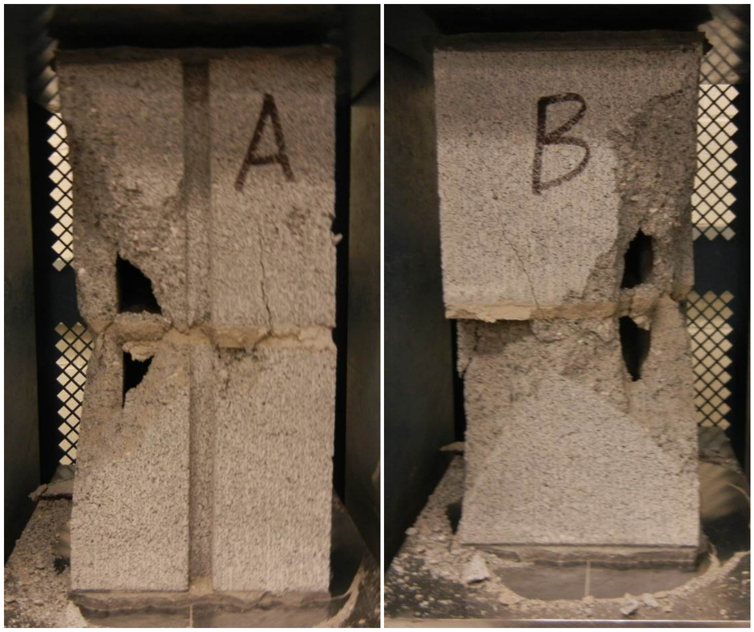

Figure 5. Example break with exposed mortar joint – adjacent faces

As Figure 5 shows, the block would sometimes exhibit a semi-conical break with the block yielding and leaving the mortar joint intact. Other types of fractures that were exhibited include conical, cone, shear, split, face shell separation and multiple combinations as shown in Figure 6.

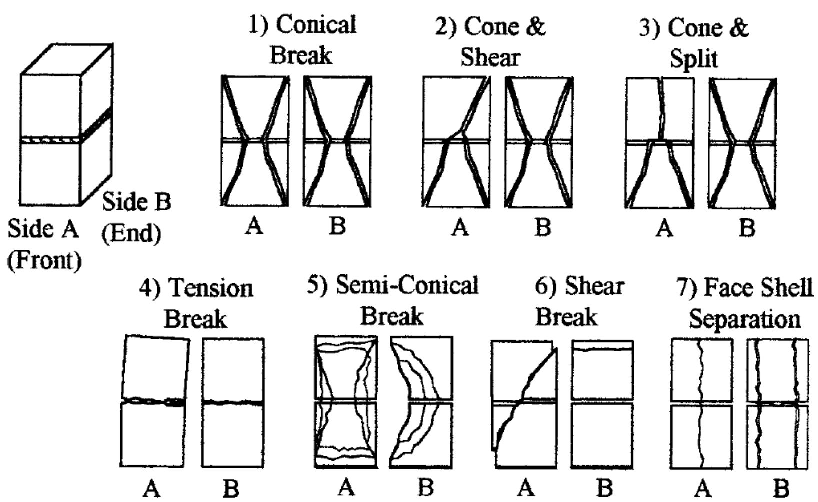

Figure 6. Failure modes from ASTM C1314-12 [9]

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Conclusions

Results from the strength performance tests indicate that recycled brick aggregate and manufacturing waste would be a suitable substitute for the standard C144 masonry sand. Specifically,

- Cube testing indicated that the demolition brick sand was 169% stronger than the natural, masonry sand while the brick manufacturing waste was 137% stronger than the natural, masonry sand.
- Prism testing indicated that demolition brick sand was 105% stronger than the natural, masonry sand while the brick manufacturing waste was weaker than the standard masonry sand at only 83% of the sands strength.

The differences between the test data provided by the cubes and the data provided by the prisms could be explained by several reasons. One reason could be a high variability in the compressive performance of the lightweight concrete masonry units used; more tests should be carried out to attempt to separate the variability of the block from actual differences in mortar strengths. Another reason could be a difference in bond strength between the mortar joint and the concrete masonry units that make up the test prism.

During the early stages of testing, there was a lack of bond strength between the mortar and the recycled aggregate. This was mediated by

- Sieving out the #4 and #8 materials from the samples before creating cubes or prisms
- Using a capping plate with a finer surface finish to minimize friction between the cap and the plate
- Extending the cure time from seven days to twenty eight days to ensure full strength development.

Sieving out the #4 and #8 materials from the crushed brick aggregates served two purposes. It improved the bond strength between the concrete masonry units and the mortar joint and improved the workability of the material. The improvement of the capping plate decreased the amount of force it took to get the specimen out of the capping apparatus. This greatly reduced the risk of cracking or damaging the prisms during this process. Lastly, extending the cure time to 28 days improved the quality of the data retrieved by letting the strength of the mortar-block interface and the overall compressive strength of the mortar develop.

Due to the inability of the recycled materials to provide satisfactory cubes using the standard brass molds used in ASTM C109-12 [14], a modified method for creating test cubes was developed. The modified cube process closely followed the established process of creating grout specimens where blocks are arranged to form cube molds that serve as porous media to mimic the moisture absorption found in the prisms.

While strength testing shows promising results, further testing beyond strength performance is required to validate these materials as viable substitutions in the building industry. Future efforts should include resistance to freeze/thaw, shear and tensile strength, and thermal performance of the recycled brick aggregates.

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