Assessing the Performance of Concrete Containing Recycled Glass on Tensile Splitting Strength and Resistance to Alkali Silica Reaction

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Abstract. Using recycled glass in concrete applications decreases the amount of glass in landfills and substitutes for expensive aggregates in the concrete mix. However, there has been a concern on recycled glass with smooth surfaces that would result in a drop in strength and in particular a reduction of an already low ductility. Thus, in many design aspects, the use of recycled glass in concrete is limited up to 30% by weight due to concern on concrete strength reduction. The current manufacturing technology in the recycling glass has been grown and evolved through which recycled glass has been processed to exhibit the following features: basically zero water absorption, excellent hardness (great abrasion resistance), high durability to resist extreme weather conditions, etc. The paper challenges the currently used recycled glass mixtures and presents new mix design principles for concrete mixed with 10%, 20%, 30%, 50%, and 100% recycled glass as replacements of nature sand and Portland cement to assess (1) strength changes and (2) resistance to alkali silica reaction (ASR). Aggregate, water reducer, hydration stabilizer, mid-range water reducer, fiber, and viscosity modifier were prepared with varying dosages of recycled glass. A series of scanning electron microscope (SEM) imaging were performed to evaluate the resistance of recycled glass specimens to ASR. The paper concludes that the use of recycled glass as an alternative aggregate and cement binder in the concrete mixtures show promising performance in both tensile splitting strength and ASR.

1 Introduction

Conventional or typical concrete is designed to have a high compression strength that can be applied to a diverse spectrum of real world projects. Approximately 7 million cubic yards of concrete are produced per year, making it the second most consumed substance on earth (next to the water) [1]. Cement production is growing by 2.5% annually, and is expected to rise from 2.55 billion tons in 2006 to 3.7-4.4 billion tons by 2050 [2]. However, conventional cement production has created substantial volumes of greenhouse gas (GHG) that have influenced the environment. Based on a report done by Portland Cement Association [3], cement plants in the U.S. accounted for about 1.1 percent of U.S. GHG emissions, 82 million
tons out of a total of 7.28 billion tons. Recently, the increasing interest in strategies to reduce (GHG) emissions has led to the examination options for reducing emissions from the production of Portland cement.

In addition to cement in the concrete mix, aggregates known as granular materials collected from natural resources, can also be used in an environmentally-friendly way for concrete construction. Aggregates typically account for 70-85 percent, by weight, of the materials used in concrete. Using recycled materials for replacement of nature aggregates would substantially lessen the disruption of the environment. One of methods is to use alternative materials to replace manmade Portland cement such as recycled glass. Pulverized post-consumer glass is eco-friendly alternative to be considered in concrete, specifically to replace the Portland cement, natural sand and gravel aggregate. However, there has been a concern on recycled glass with smooth surfaces that would result in a drop in strength and in particular a reduction of an already low ductility. Thus, in many design aspects, the use of recycled glass in concrete is limited up to 30% by weight due to concern on concrete strength reduction [4]. However, the current manufacturing technology in the recycling glass has been grown and evolved through which recycled glass has been processed to exhibit the following features: basically zero water absorption, excellent hardness (great abrasion resistance), high durability to resist extreme weather conditions, etc. In addition, many researchers have investigated the use of recycled glass as fine and coarse aggregate of the concrete in the past years [5]-[7]. More recently, research works have been started using recycled materials in concrete mixtures in 2012 [8]-[9]. If recycled glass can be used as a replacement of aggregate and cement, the effort to reduce the carbon dioxide due to production of virgin aggregate and cement will be significant. Furthermore, recycled glass (RG) is a product that acts as a pozzolan material. The presence of pozzolan in a concrete mix can help consume the alkali that are produced from the cement and the aggregate in the mix which in overall helps to reduce the amount of ASR within the concrete structure. Thus, the purposes of this paper is to present a list of concrete mixtures using recycled glass as an alternative aggregate and cement binder and evaluate the effectiveness of recycled concrete mixtures in the performance of strength and resistance to alkali-silica reaction.

2 Material preparation

Two types of recycled glass were used in experiments including coarse recycled glass (RG sand) and fine recycled glass (RG powder as a replacement of cement binder). Based on literature findings, we would like to challenge the currently used recycled glass mixtures and present new mix design principles for concrete mixed with 10%, 20%, 30%, 50%, and 100% recycled glass as replacements of nature sand and Portland cement. Based on the goal of achieving desired high strength of recycled glass concrete, we used a number of mix formulas to produce a volume of 600 cubic inch/9,832 cubic centimeter concrete mixed with and without fiber. The mix design formula contained recycled glass, coarse aggregate (1/2", 3/8” and No.4), admixture (Water Reducer, VMA900, Air Entrainment and polymer), water, cement, and sand. Recycled glass powder was used to replace cement while coarse recycled glass was used to replace nature sand. The coarse aggregate (1/2", 3/8” and No.4) remain unchanged in the mixing process. Table 1 shows the design mix matrix containing a variety of ranges using recycled glass. It should be noted that Control 1 mix design in Table 1 containing 100% cement and 100% natural aggregate (sand) was used as a control group in order to compare strength difference with the rest of mix designs containing different percentages of recycled glass.
In addition to aggregate/cement or aggregate/cement replacements, admixtures were also an important resource in the concrete mixture used to improve strength and to provide the design mix with resistance against thermal and fatigue cracks. The admixtures used in the all mix designs are mid-range water reducer, air entrainment (Micro Air), viscosity modifier (VMA), and polymer. Water reducer is a chemical that reduces the amount of water needed for the mix to reach its high strength. This chemical improves the strength of the concrete mix (compression and tensile), as well as the workability of the concrete. Air entrainment creates air bubbles in the concrete structure to facilitate resistance to thermal expansion and contraction of the concrete. Viscosity modifier also helps to increase the strength and the workability of the concrete mix. All specimens were produced using the mix design matrix depicted in Table 1 and placed in a 4 x 8 inches (15 x 30 cm) cylinder. All demolded specimens were subsequently submerged in a water tank for curing until the 7th days and the 28th days for testing.

3 Material testing and result discussions

3.1 Tensile splitting test

A tensile strength test was used to evaluate the behavior of the concrete under applied load. The testing procedure follows the American Society for Testing and Materials ASTM C496: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens [10]. The testing device, a specimen set up, and a close view of a tested specimen are shown in Figure 1. The primary reason for testing splitting strength instead of compression was to review the usefulness of recycled glass in the concrete pavement structure (both airfield and highway systems). So, the interest of research was focused on tensile splitting performance than compressive strength of recycled specimens.
The test results were categorized into two groups for comparison. Mixtures containing less than 50% RG replacement are shown in Table 2 while mixtures containing greater than 50% RG replacement are shown in Table 3. In comparison with the specimens containing less than 50% RG replacement, the specimens containing more than 50% RG replacement matrix (MD# 1.7-MD# 1.9) have better splitting strength. When the amount of RG increases and it is more consistent in distribution throughout the matrix in the concrete, the strength of concrete specimens increased in the twenty-eight (28) days with the average strength of 4.71 MPa to 5.47 MPa. In the design mixes that contain less than 50% RG replacement, MD# 1.4 with a 20% RG as a cement binder replacement has the least tension strength tested at 28 days. On the other hand, for the design mix with RG replacement higher than 50%, the MD# 1.7 specimen (50% RG sand) has the highest strength (28 days) among all specimens. From Table 2 and Table 3, it seemed that the role of recycled glass with a replacement of coarse aggregate (sand) could exhibit better strength improvement than the fine RG power (as an alternative cement binder). Regardless of designs with RG higher and lower than 50%, both tensile strength values did not surpass the control group’s strength (28 days). However, the overall strength of recycled glass specimens still meet the desired strength requirement of 2.76 MPa, a desired level of splitting strength for most concrete pavement structure.

### Table 2. Tensile Tension Strength for mixes less than 50% RG replacement

| Experimental Number | Experimental Detail  | 7 days average (MPa) | 28 days average (MPa) |
|---------------------|----------------------|----------------------|----------------------|
| Control             | 0% RG                | 4.38                 | 6.14                 |
| MD# 1.1             | 30% RG Sand          | 5.31                 | 5.58                 |
| MD# 1.2             | 30% RG Cement        | 4.69                 | 4.86                 |
| MD# 1.3             | 20% RG Sand          | 3.88                 | 4.72                 |
| MD# 1.4             | 20% RG Cement        | 5.48                 | 3.90                 |
| MD# 1.5             | 10% RG Sand          | 4.03                 | 4.83                 |
| MD# 1.6             | 10% RG Cement        | 4.41                 | 4.38                 |
| Average strength (#1.1 ~1.6) |                     | 4.63                 | 4.71                 |
2.76 MPa overall strength of recycled glass specimens still tensile strength aggregate (sand) Table 2 and Table 3, it seemed that the 1.7 specimen days with a 2 MPa to 5.4 and it is more con matrix less than 50% RG replacement 50% RG replacement less than

Fig. The test results were categorized in to two groups for comparison. Mixtures containing 1. On the other hand, for the design mix with RG replacement higher than 50%, the Average strength (#1.1 ~1.6) 4.71 5.65

| Experimental Number | Experimental Detail       | 7 days average (MPa) | 28 days average (MPa) |
|----------------------|---------------------------|----------------------|-----------------------|
| MD# 1.7              | 50% RG Sand               | 4.79                 | 5.72                  |
| MD# 1.8              | 50% RG Cement             | 4.31                 | 5.03                  |
| MD# 1.9              | 100% RG Sand              | 4.48                 | 5.65                  |
| Average strength (#1.7 ~1.9) |                     | 4.53                 | 5.47                  |

3.2 Evaluating resistance to alkali-silica reaction

Alkali-silica reaction (ASR) is a reaction that caused by the silica within the aggregates and cement that over time turn into a gel. As time passes, more gel is formed causing it to take more space, causing micro cracks and reducing its tensile strength [11]. Specifically, the ASR mechanism can be divided into two parts: (1) critical components for creating ASR, and (2) the actual chemical reaction and ASR distress expansion.

(1) Three critical components are essentially to produce ASR:
   i. Aggregates that contain reactive silica or silicate chemicals.
   ii. Sufficient alkali ions such as sodium (Na) and/or potassium (K).
   iii. Sufficient water/moisture inside the Portland Cement Concrete pavement.

(2) The actual chemical reaction and distress mechanism of ASR can be formed by the following steps:
   i. The actual chemical reaction:
      Siliceous (aggregates) + alkali (mortar/cement paste) + water (intrusion/moisture environment) = ASR gel, a viscous material.
   ii. ASR gel product + moisture (absorption of water) → expansion surrounding cement paste.
   iii. Stresses inside pavements created by expansive forces eventually result in cracking and spalling distress.

It is recognized that the product of the chemical reaction is the ASR gel which subsequently absorbs moisture, expands, and eventually causes concrete to crack and weakens the integrity of a concrete structure.

3.3 Scanning electron microscope imaging

Scanning electron microscope (SEM) imaging was performed using specimens that were prepared for alkali silica reaction to observe the silica gel resistance. The SEM imaging is implemented to evaluate the resistance of recycled glass to silica gel. The SEM was done in the Microanalysis Core Facility located at Northern Arizona University. Before SEM imagining, all specimens were coated with plutonium (Pu) and gold (Au) to enhance the resolution of the imaging on the specimens. The mix designs that the test was performed on were selected from Control 1, MD#1.1, MD#1.2, MD#1.3, MD#1.4, and MD#1.5 in which % of RG was less than 30%. The specimens were added silica to enable ASR affection in individual concrete specimen.
In order to observe how ASR gels are produced within specimens, all ASR specimens were undergone a series of SEM screening to allow us observing the appearance of ASR gels on the specimens. The electron microscope device is capable of filtering out the amount of individual chemical element and showing in different colors on the screen (Figure 2). This helps us better understand the effectiveness of recycled glass in mitigating ASR gels among all specimens.

![Silica gel represented in MD 1.3 (L) and MD 1.4 (R).](image)

**Fig. 2.** Silica gel represented in MD 1.3 (L) and MD 1.4 (R).

After ASR occurred on all specimens, SEMs were able to measure a percentage of individual chemical contribution to the total weight in each specimen. The measure data allowed us to review the level of ASR affection on specimens based on the percentage of recycled glass used in the concrete mix. The results are presented in Table 4. Since ASR is primarily triggered by alkali, silica, and calcium elements (highlighted in yellow in Table 4), the main focus was to pay attention on the % weight that was generated by ASR on each specimen so enabling us to evaluate the effectiveness of recycled glass in mitigating ASR in the concrete mix. As shown in Table 4, it is clear that control group (without the use of recycled glass) generated the highest ASR gels among other specimens mixed with recycled glass. The MD-S 1.3 specimen (20% RG sand) has the least ASR gels remained on the specimen. In comparison with the use of coarse recycled glass in all specimens, the addition of fine recycled glass power in the concrete mix as an alternative cement binder seemed not to have better resistance to ASR affection. This finding suggests that the addition of coarse recycled glass in the conventional concrete mix could increase the ability to resist ASR occurrence in the concrete structure. However, more research works should be done to further verify the results done in the research.

**Table 4.** Measure results of individual chemical element within specimens.

| Specimen # | O-K | Mg-K | Al-K | Si-K | Ca-K | Pd | Au | Total |
|------------|-----|------|------|------|------|----|----|-------|
| Control    | 0   | 0    | 0    | 48.45| 31.55| 0  | 0  | 100   |
| MD-S 1.1   | 35.57| 0.38 | 3.03 | 8.77 | 30.78| 10.27| 11.19| 100   |
| MD-S 1.2   | 0.64 | 0    | 0    | 25.00| 2.16 | 51.67| 20.53| 100   |
| MD-S 1.3   | 3.80 | 0    | 1.80 | 0.79 | 8.0 | 31.51| 54.91| 100   |
| MD-S 1.4   | 21.21| 1.01 | 1.30 | 9.32 | 31.65| 13.51| 22.01| 100   |
| MD-S 1.5   | 1.66 | 0    | 0    | 4.48 | 18.15| 25.20| 50.51| 100   |

Note:
4 Conclusions

The paper presents the use of recycled glass in the concrete mix to promote the eco-environmental application of alternative materials in concrete production. The paper has the following conclusions:

1) Even though all specimens mixed with varying amounts of recycled glass did not exceed the control group (without recycled glass), however, the tensile splitting strength of all recycled glass specimens still show promising results ranging from 3.90 MPa to 5.72 MPa, higher than the desired level of 2.76 MPa (400 psi) splitting strength for most concrete pavement structure.

2) Based on SEM analysis, the resistance of recycled concrete mixtures to ASR is considered satisfactory as compared with the control group.

3) The use of coarse recycled glass as a sand replacement shows better performance than the fine recycled glass (as a cement binder replacement) in strength and ASR resistance.

4) The replacement of recycled glass with #4 or higher coarse aggregate sizes is worth testing for future research work.

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