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# The Use of Recycled Glass in Concrete

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## Introduction

There are large amounts of recycled glass available for use in concrete, but there have been many notable failures in concretes containing recycled glass due to unusual chemistries that occur when glass is included in a concrete mix. This paper discusses these interactions and provides remedies to safely use recycled glass aggregates and some glass powders in concrete mix designs.

First, some definitions:

- **Concrete** — a mixture of cement, aggregates, water, and supplementary cementing materials (SCMs), also known as *pozzolans*.

- **Pozzolan** — an amorphous (glassy) powdered siliceous material that responds to the alkali content in cements to react with lime in the high pH environment in concrete to form additional CSH (calcium silicate hydrate) binder within the pore structure of the concrete. Pozzolans are effective as minus 325 mesh powders. Pozzolans vary widely in reactivity, color, water demand, and in chemical composition. Much of the chemistry associated with certain pozzolans, such as sulfides, carbon, sulfates, and alkalis can be quite deleterious to the long-term durability of concrete.

- **Recycled glass** — comes from a variety of sources including curbside pickup, fiberglass factories, and other mixed glass recycling centers. Glass has a chemistry that can be (a) soda lime glass (bottles or windows) with 10-15% alkali content; (b) reinforcement fiberglass with 1% alkali content; or (c) borosilicate glass (Pyrex) with 12% boron and 4% alkalis. Aggregates made from soda lime glass can be used in concrete if properly mitigated for ASR, as discussed later. Powders made from reinforcement fiberglass are excellent pozzolans. Borosilicates should never be put in concrete due to their extreme expansion in concrete environments. The wide range of chemistries found in common recycled glass is shown in Table 1.

- **Alkalis** — are the sodium and potassium oxide ($Na_2O$ and $K_2O$) constituents of glass or cement that cause the pH in concrete to reach 13.5 or higher. Alkalis, reacting with certain susceptible aggregates, are the main cause of ASR (alkali silica reaction), so many manufacturers' Portland cements are sold as low alkali (less than 0.6% alkali) to minimize ASR. Many white cements have alkali contents below 0.2%.

- **Lime** — is the calcium hydroxide formed when water is added to Portland cement. More than 20% of the water + cement paste turns into lime. This lime is the primary source of efflorescence.

- **ASR** — the alkali silica reaction, which causes an expansive silicate gel to form with reactive aggregates present in concrete. Reactive aggregates include glass, flint, chert, or certain rhyolites. The expansive force of the silicate gel is greater that the tensile strength of concrete, so the concrete will crack. Depending on the reactivity of the aggregate and the alkali content of the cement, cracking can occur as early as days, or it can be delayed for many months or even years later. As cracking occurs, more water enters the interior of the concrete to mobilize the alkalis present. In severe cases, over the years, ASR cracking can destroy the strength of the concrete and ultimately reduce it to rubble.

**Table 1. Chemical Composition of Recycled Glass Types**

| | SODA LIME | | SPECIALTY | | |
|---|---|---|---|---|---|
| **Consti-tuents** | **Container (Bottle)** | **Window (Float)** | **E-Glass (Fiber)** | **Borosilicate (Pyrex)** | **Panel (TV)** |
| $SiO_2$ | 74 | 73 | 50-55 | 65-85 | 62-85 |
| $Al_2O_3$ | 1.3 | 0.15 | 15-20 | 1-5 | 0.5-2.5 |
| CaO | 10.5 | 9 | 20-25 | 0-2.5 | 0-4.5 |
| MgO | 0.2 | 5 | <1 | .. | 0-2.7 |
| $Na_2O$ | 13 | 14 | <1 | 3-9 | 6-11 |
| $K_2O$ | 0.3 | 0.03 | <0.2 | 0-2 | 4-7 |
| $B_2O_3$ | .. | .. | 0-6 | 8-15 | .. |
| Others* | 0-2[(a)] | 0-2[(a)] | 0-2[(b)] | 0-1[(c)] | ~20[(d)] |

* (a) $Fe_2O_3$, $Cr_2O_3$, $MnO_2$, $TiO_2$, $SO_3$; (b) $Fe_2O_3$, $TiO_2$; (c) BaO; (d) BaO, SrO, $Fe_2O_3$, $TiO_2$, $CeO_2$, $ZrO_2$, PbO, ZnO, $As_2O_3$, $Sb_2O_3$

- **CSH** — is calcium silicate hydrate, the main binder formed in concrete when water is added to Portland cement. It either forms from the initial reaction of adding water to cement powder, or later from the reaction of a pozzolan with the lime also present in every Portland concrete. The formation of CSH continues over a span of years as more cement hydrates or more pozzolan reacts. As time passes, the concrete becomes harder, denser, stronger, and is less porous.

With the definitions out of the way, we can examine the issues of using recycled glass as aggregates or pozzolans in concrete.

## General Pozzolan Information

For a pozzolan to work to remediate ASR, it must be quite effective in powdered form (minus 325 mesh), and it must not bring unacceptable chemical constituents to the reaction. Deleterious chemical constituents include sulfides (turn concrete green), sulfates (can cause delayed expansion), and alkalis (which add more alkali to concrete which creates higher risk of ASR over the life of the concrete). A pozzolan can be thought of as a *sacrificial anode*, as it depolymerizes at the 13.5 pH environment of freshly poured concrete to go into solution to ultimately react with the lime in solution to form additional CSH binder. The widely dispersed presence of the pozzolan will consume (sequester) the alkalis in concrete such that the reactive aggregate remains untouched because of its larger particle size and the sacrificial characteristics of the pozzolan. A good pozzolan functions both to mitigate ASR and to consume the lime to greatly reduce efflorescence.

This brings up the issue of pozzolan chemistries and sources. There are large amounts of mineral processing slags, coal fly ashes, recycled glasses, and other amorphous materials that all undergo with varying effectiveness the pozzolanic reaction to react with the lime in concrete. The problem is their level of effectiveness and the chemical constituents they introduce to the mix. For instance, most slags contain sulfides and have widely varying reactivities, and each must be individually tested to determine whether the side effects are acceptable. Similarly, fly ashes vary widely in composition and fineness and many contain carbon, sulfates or lime, which may create undesirable effects in concrete. Silica fume and metakaolin are widely used, but they have high water demands and greatly affect concrete workability and placement rheologies.

## Recycled Glass as a Pozzolan

The issue of recycled glass is quite complicated from a chemistry point of view (Table 1). Years ago, the reinforcement fiberglass manufacturers saw a large market potential in using glass reinforcements as reinforcing fiber in concrete. Early tests soon indicated that normal chemistry reinforcement fiberglass almost totally dissolved in the concrete environment, as the extremely low alkali content of the fiber glass, about 1%, caused it to be highly susceptible to alkalis in concrete environments. The fiberglass manufacturers were able to address the problem by adding 16% zirconia to the glass chemistry to make it alkali resistant (so called AR glass). Borosilicate (Pyrex) type glasses are so expansive that they were selected to be the ASTM C441 test aggregate that severely tests the ASR mitigation capability of various pozzolans. Under no circumstances should borosilicate glass be added to concrete. Soda lime plate and bottle glass are reactive aggregates and must be mitigated with pozzolans and/or lithium compounds.

Understanding the need for a pozzolan to be sacrificial, the phenomena of the quick reaction (in alkaline environments like concrete) of fiberglass led to the development of pozzolan powder derived from this same reinforcement fiberglass, called VCAS White Pozzolan. VCAS, a patented product, has been shown to be very effective, is as white as white cement, and has a very low water demand. VCAS has an optimum ratio of Ca, Si and Al ions to react with lime to form CSH and CASH. Further, there is no chemical baggage associated with VCAS in the form of sulfides, sulfates, carbon, heavy metals, or high alkali content. It reacts quickly and can be used at a 20% cement replacement level to completely mitigate ASR reaction, even in cements with 1% or higher alkali contents. As the VCAS reacts with lime, the product, CSH, precipitates within the pore and void structure of the concrete structure, densifying the concrete and mitigating secondary efflorescence (a process that starts occurring several days after placement).

Over the years, it naturally occurred to many to grind up bottle or plate glass to minus 325 mesh for use as a pozzolan. However, an incomplete understanding of the chemistry, especially the delaying effect of high alkali reactions taking place, caused several problems. First, it takes much higher loadings and longer time frames for a pozzolan made from bottle glass to offer sufficient ASR mitigation. Perhaps the more serious problem, longer term, is that bottle glass powder does eventually react, releasing high quantities of alkali into the concrete matrix to further aggravate ASR conditions with reactive aggregates. Why would cement manufacturers work so hard to make low alkali cements less than 0.6% alkali, then see a bottle glass pozzolan containing up to 15% alkali (25x that of cement) replace some of the cement? Chemically speaking, high alkali pozzolans create a long running battle to fix problems created by themselves. The more a bottle glass sacrifices itself, the more problems it causes.

The key role of a pozzolan is to chemically tie up (sequester) alkalis ($Na_2O$ and $K_2O$) to keep them from reacting with susceptible aggregates. In doing so, they also react with lime. Since bottle glass used as a pozzolan is already loaded up with alkalis, its capacity to tie up more alkalis is limited compared to very low alkali pozzolans like metakaolin, silica fume and VCAS made from reinforcement fiberglass (Table 1). Therefore, it takes much more bottle glass powder as a cement replacement to mitigate ASR. Adding all the extra bottle glass pozzolan required creates another set of problems. First, the more pozzolan that is added retards strength development in the concrete to an unacceptably low rate. Secondly, as the bottle glass powders do react, they add more alkalis in the form of sodium silicate (aka water glass) to the concrete, which are highly soluble and can migrate to the surface in the form of sodium efflorescence.

## Recycled Glass as an Aggregate

Recycled glass is a reactive aggregate that is very prone to the deleterious alkali-silica reaction (ASR). ASR remediation is best accomplished by the use of a pozzolan to replace 20-30% of the cement, or from lithium compounds that work by preferentially forming a non-expansive gel in the concrete matrix. ASR can also be mostly prevented by using extremely low alkali content cements, or by placement of concrete in a totally dry environment where moisture cannot get to the concrete either as rain, high humidity, or wet gravel under the placement.

Regarding making glass aggregates from recycled bottle glass, the same phenomena of delayed reaction of bottle glass in ASTM C441 can be observed. ASTM C441 takes a mortar bar specimen and places it in a 1M hot alkali solution for 14 days to measure ASR expansion. The control is aggregate made from Pyrex, an extremely expansive glass. The Pyrex fails well before 14 days, the normal duration of the test. The bottle glass aggregate also fails, but only after more than 50 days. This again indicates the much lower reactivity of bottle glass in cement, but it is important to note that without mitigation, under the right conditions, RECYCLED BOTTLE GLASS AGGREGATES EVENTUALLY FAIL. However, with proper mitigation with VCAS pozzolan at a 20% cement replacement level, there will be no ASR failure with recycled bottle glass aggregates. Mitigation can also be effected with silica fume, metakaolin, Class F fly ash, or lithium compounds. Interestingly, Class C fly ash will not adequately mitigate ASR for many of the same reasons that bottle glass powders will not mitigate.

## Concluding Remarks

In conclusion, recycled glass aggregates can be safely used in concrete mix designs as long as the ASR potential is mitigated with a proper chemistry pozzolan and/or a lithium compound. VCAS White Pozzolans can be used effectively in decorative concretes to both mitigate ASR and secondary lime efflorescence. These mitigations add substantially to the durability of the concrete piece as well as color fastness of the surface.

For further information see:

1. VCAS White Pozzolan TDS
2. Recycled Glass Sands TDS
3. Use of VCAS for Mitigation of ASR with PC Glass Aggregates