Towards Better Understanding of the Amorphous Silica – Alkali Reactions and the Means of Preventing Glass Aggregate Expansion in Concrete

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ABSTRACT

The effect of quantity and characteristics of the components of amorphous silica – alkali reactions, based on the research carried at the CSIRO Laboratories in Australia and by the author are discussed. Conditions under which the expansion of silica-gel can be reduced to a safe level or even completely eliminated are presented. The emphasis is made on the commercially viable and the most economical means of the safe use of crushed soda-lime glasses (which account for about ninety percent of all manufactured glasses) as an aggregate in structural, durable and dimensionally stable concretes, in which hydraulic cements are used as a binder. With the depletion of good quality natural aggregates from quarries located in the proximity of construction and development sites, the use of recycled materials becomes particularly important in the current climate of global recession. It should be emphasized, however, that the results of these findings may not be universal, and when applied to the specific local conditions (both – glass and hydraulic cements) should be verified in the laboratory tests.

SODA-LIME GLASS – POTENTIAL FOR RECYCLING

Pure silica, SiO_2 has a "glass melting point" of over 2300^{o}C. Addition of sodium carbonate, Na_2CO_3 lowers the melting point to 1500^{o}C and results in production of soda-lime glass, which is the most common of the manufactured glasses. Typical composition of soda-lime glass is as follows: 74% SiO_2, 13% Na_2O, 10.5% CaO, 1.3% Al_2O_3, 0.3% K_2O, 0.2% SO_3, 0.2% MgO, 0.01% TiO_2, and 0.04% Fe_2O_3. There are numerous standards for glass in different countries of the world, such as ASTM D 5359-98 (2004) Standard Specification for Glass Cullet Recovered from Waste in Manufacture of Glass Fiber, and the German Standard: DIN 1259, Begriffe für Glasarten und Glasgruppen, (1986), to name just a few. The glass component in municipal waste usually includes bottles, broken glassware, light bulbs and other less common items made of glass. In many developed countries of the world both industrial and household waste is separated into recycled and disposable components. Glass collection points, the so called

“Bottle Banks”, are commonly placed in the United Kingdom near places of human activity and concentration. In most European countries refillable bottles comprise the main bulk of the recycled glass. Some 750,000 tons of glass was lately recycled in the UK annually, and more than two million tons in Germany. Unfortunately not all the disposable glass can be effectively recycled in many countries of the world, and this provides an opportunity to use crushed glass as an aggregate in concrete. There are already Standard Specifications to which recycled glass must comply. In the UK these are: British Standards Institute PAS 101, Recovered container glass, Specification for quality and guidance for good practice in collection (2005), and British Standards Institute PAS 102, Specification for processed glass for selected secondary markets (2005).

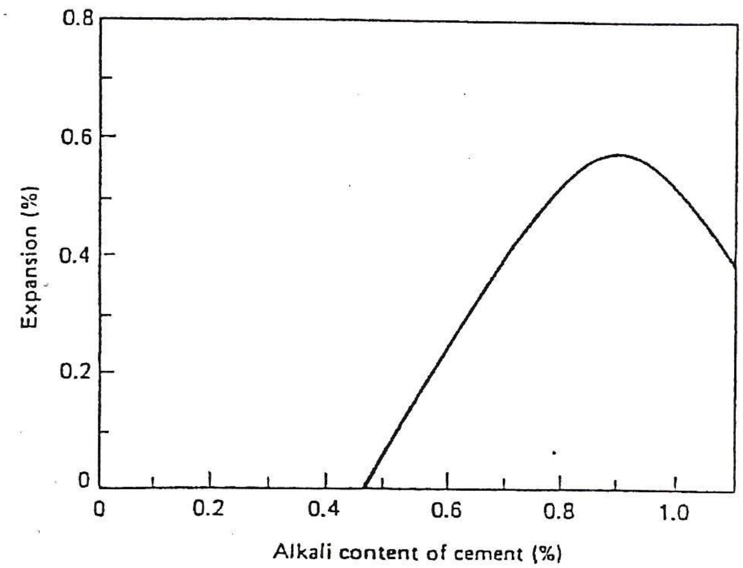
REQUIREMENTS FOR PROPER USE OF GLASS IN CONCRETE

As already mentioned above, the soda-lime glass, if properly separated from other waste, washed and crushed has the potential of being used as an aggregate in concrete. The main obstacle to utilization of glass in concrete made with hydraulic cements is the tendency of this amorphous silica material to expand in presence of alkalis, thus creating internal stresses which can, and usually do result in cracking and spalling. This distress not only reduces the load bearing capacity of structural members, but it can lead to the ingress and attack by acids and/or carbon dioxide on steel reinforcement, causing it to corrode. Most Portland cements contain small, but measurable amounts of alkalis in the form of sodium and potassium oxides. The content of alkalis varies, depending on the raw materials used in Portland cement manufacture, and it is usually limited in most Standard Specifications to well below one percent. Thus, for safe and successful use of glass aggregate in concrete it is essential to reduce, and preferably to completely eliminate the potential for coarse aggregate to expand in the presence of alkalis which, almost without exception, are present in all hydraulic cements. To do so, we must have clear understanding of the real meaning of the amorphous silica – alkali reactions.

NATURE OF THE AMORPHOUS SILICA – ALKALI REACTIONS

Alkali-Silica Reaction (ASR) is a reaction in concrete between amorphous silica (such as soda-lime glass) and an alkali, the main source of which is usually Portland cement.
This reaction results in formation of a gel, the volume of which, in presence of moisture, increases over a period in time. If gel is present in relatively large local concentrations and if it is restrained by the adjacent matrix and/or aggregate, significant internal pressures can be developed in concrete. As concrete is relatively weak in tension these pressures usually lead to concrete failure in a form of cracking and spalling. The factors affecting formation and expansion of gel, as a result of alkali-silica reactions, were investigated in the early 1950-s at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Melbourne, State of Victoria, Australia. The results of this very comprehensive research were reported by Vivian [1951]. In my opinion, three of the most important features of this investigation are shown in the following Figures.

First (Figure 1) represents the relationship between the alkali content of concrete and its expansion when all the other ingredients and proportions of concrete remain constant.



The significant part of this result is the non-linear relationship between expansion and the alkali content. Again, for the constant amorphous silica presence in a given concrete, there is a maximum expansion at certain alkali content in concrete, after which the expansion decreases. The significance of this result I shall discuss in conjunction with the results shown in the other two Figures

Figure 1 Expansion vs alkali content

The relationship between expansion of concrete and the reactive silica content (in our case the amount of soda-lime glass) is also non-linear. (Please refer to Figure 2). It is most significant, that at constant alkali content the expansion is reduced to zero, when the reactive silica component of concrete is increased beyond a certain percentage. Thus, there seems to be a potential to completely eliminate adverse expansion of concrete in which reactive silica (soda-lime glass) is present.

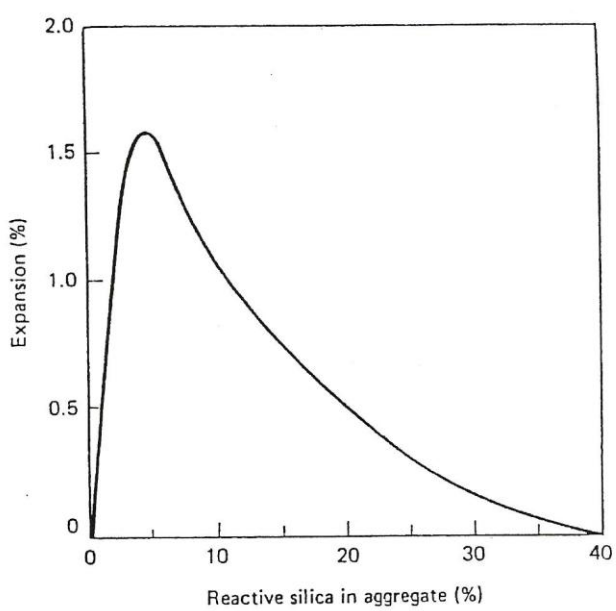


Figure 2 Expansion vs reactive silica content

Another important feature (Figure 3) is the effect of aggregate size on the expansion, when both the alkali and the reactive silica contents remain constant. As can be seen, with the reduction in the aggregate size the expansion originally increases and, after reaching a maximum, value, starts to diminish.

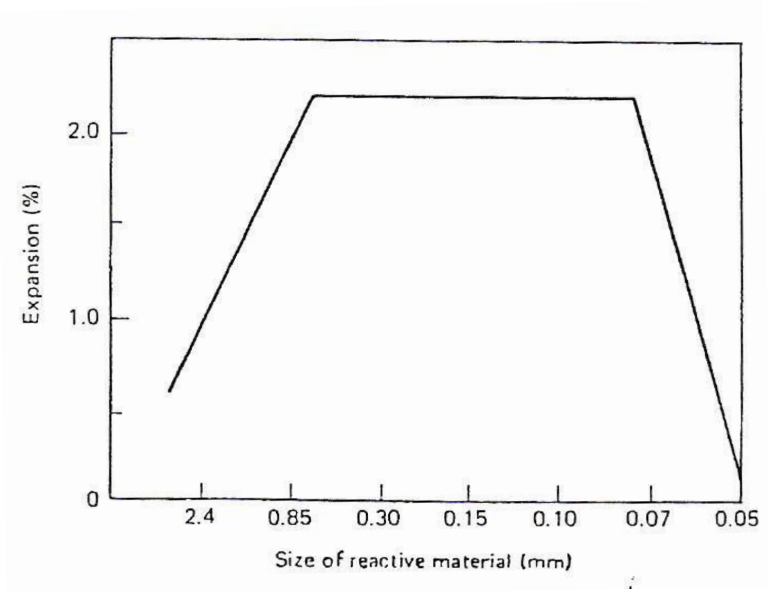


Figure 3 Expansion vs size of aggregate

RESEARCH INTO THE EFFECT OF GLASS AGGREGATE IN CONCRETE

An extensive research project into the properties of concrete containing glass aggregate was conducted in the late 1970-s at the University of New South Wales, Australia, by Samarin, [1980]. A detailed study was carried out into the properties of four different concrete types. Control mix contained no glass. Crushed river gravel was used as coarse aggregate and river sand as a fine fraction. In the second mix sand fraction was replaced with crushed glass of similar grading to that of sand. In the third mix, containing "glass sand", part of Portland cement was replaced with "glass dust". This was glass pulverized to fineness which was similar to that of Portland cement. Finally, in the fourth mix "glass dust" was replaced with good quality fly ash. The ratio of all the ingredients in all four mixes was kept as constant as possible, concurrently ensuring the correct yield of each concrete mix (in kg/m^3). Properties of both fresh and hardened concretes were investigated. Water to "cementicious" ratios were in the range of 0.56 to 0.59, with the corresponding consistencies, as measured by slump (mm) between 60 and 80. Control mix was at the lowest slump and fly ash mix the highest. In order to confirm that pulverized glass was indeed a pozzolanic material, X-ray Powder Deffractometry tests were performed by Samarin [1980]. Samples of hardened concrete from the control mix (No.1) and from the mix containing "glass sand" and "glass dust" (No.3), were placed in a micro-wave oven and, after the breakdown of matrix, hardened paste fraction was separated and ground to cement fineness in an agate grinder.

The diffraction patterns of these two powders are shown in Figure 4. National Bureau of Standards Tables were used for conversion of X-ray diffraction angles to interplanar spacing. The absence of line at 9.80 Å in the specimen containing glass (B) which, when present, represents calcium silicate hydrate of high CaO/SiO_2 ratio, confirmed that pulverized glass was indeed a pozzolana. Also, portlandite, or $Ca(OH)_2$, which is characterized by the distinct lines at 4.90, 2.628, 1.927 and 1.796 Å – the lines which were reduced in the sample containing glass was yet another confirmation of the pozzolanic nature of pulverized glass.

Figure 4 Scanning electron microscopy

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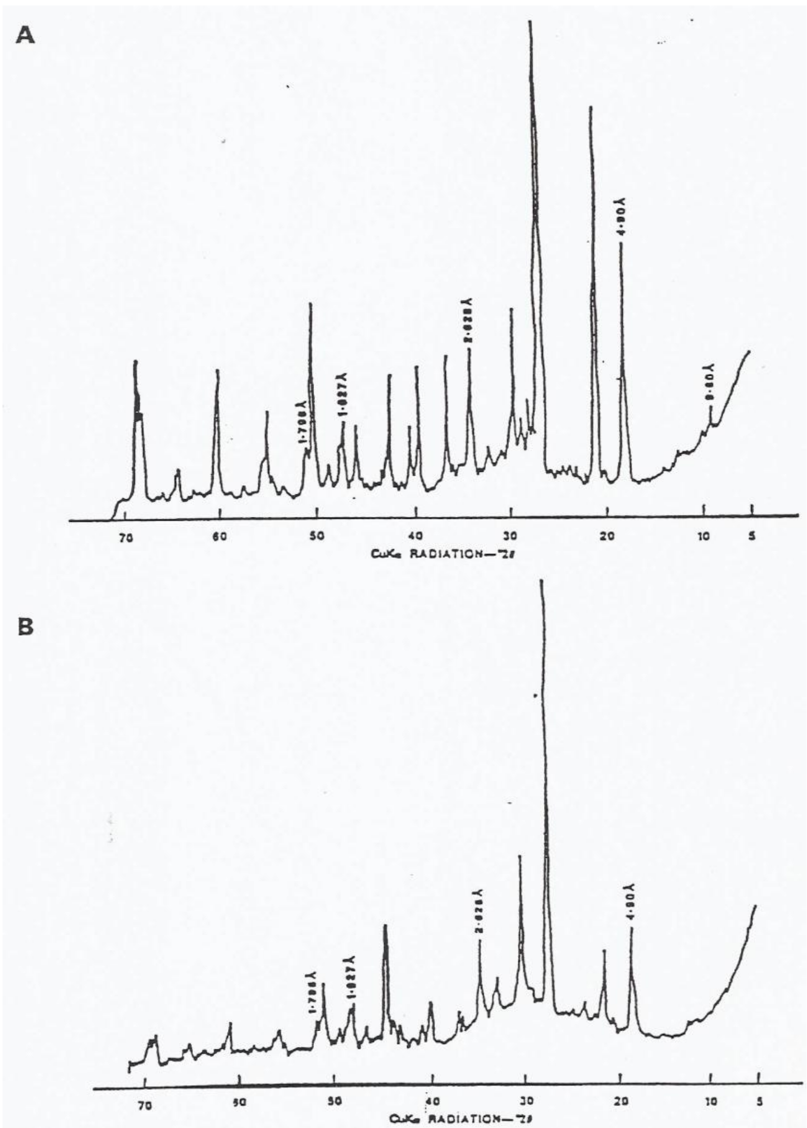

Scanning Electron Microscopy was also used to study the condition of the glass aggregate particles, in order to confirm the absence of distress due to the potential ASR.

Properties of hardened concrete of all four concrete types were comparable.

Compressive strength was evaluated at 7, 28, 90, and 210 days. At seven days all mixes exhibited strength of 26 MPa. The subsequent gain of strength was significantly better for mixes which contained glass and fly ash. At 210 days compressive strength of control mix was 45 MPa, and all the remaining concretes reached strength of 58 MPa. Tensile strength was measured only at 28 days, using “Brazil” test. Again, “plain” control mix was slightly lower at 4.1 MPa and concrete with “glass sand” and fly ash was the highest at 4.5 MPa.

Elastic Modulus was measured at 28 days with the control just slightly below the other three mixes. Ultra Sonic Pulse Velocity was evaluated at 7, 28 and 90 days. It ranged from 4.38 km/sec for the plain control and 4.46 km/sec for “glass sand” and fly ash (the highest) at 7 days. The corresponding values at 90 days were 4.59 km/sec for the control, and 4.73 (again the highest value) for mix No.4. Thus, concrete containing glass behaved very comparably with mixes in which Portland cement is partially replaced with the “optimum” proportion of good quality pozzolanic material.

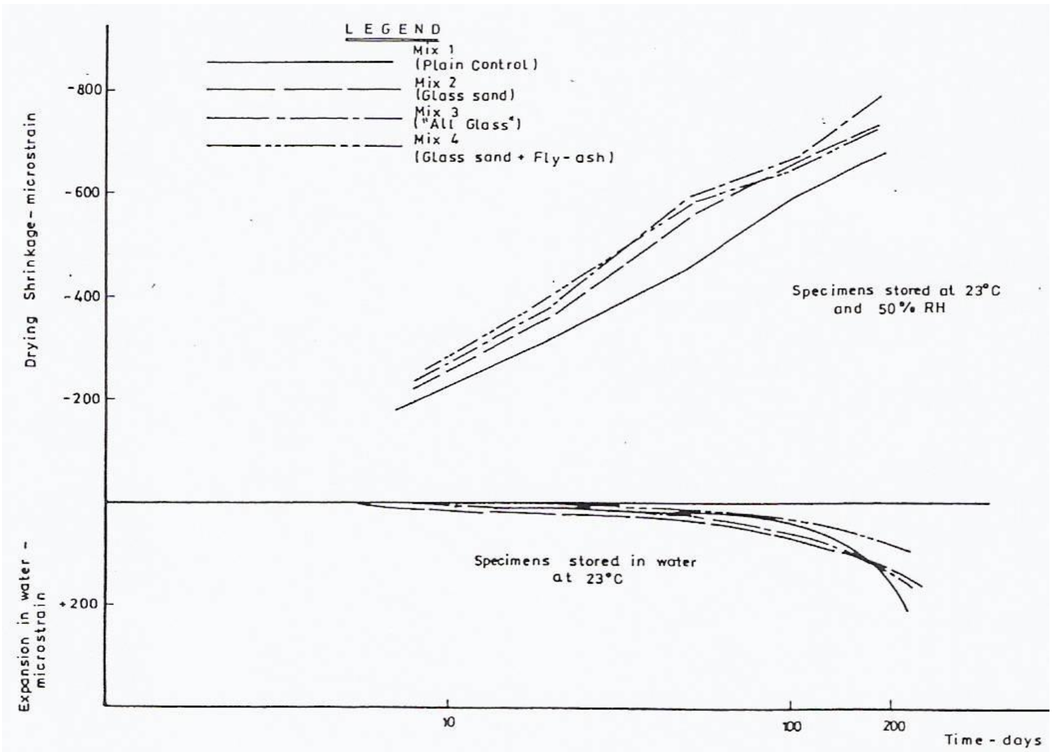

Figure 5 Dimensional stability of concrete specimens

Concrete shrinkages at 23°C and 50% relative humidity and concrete expansion of specimens continuously stored in lime saturated water at 23°C are shown in Figure 5. The results are comparable for all four concrete types, with “plain” control mix exhibiting slightly lower shrinkage, but expanding somewhat more in water at 200 days.

In addition to shrinkage tests and continuous storage in water, specimens were subjected to the alternative cycles of wetting and drying. The results are shown in Figure 6.

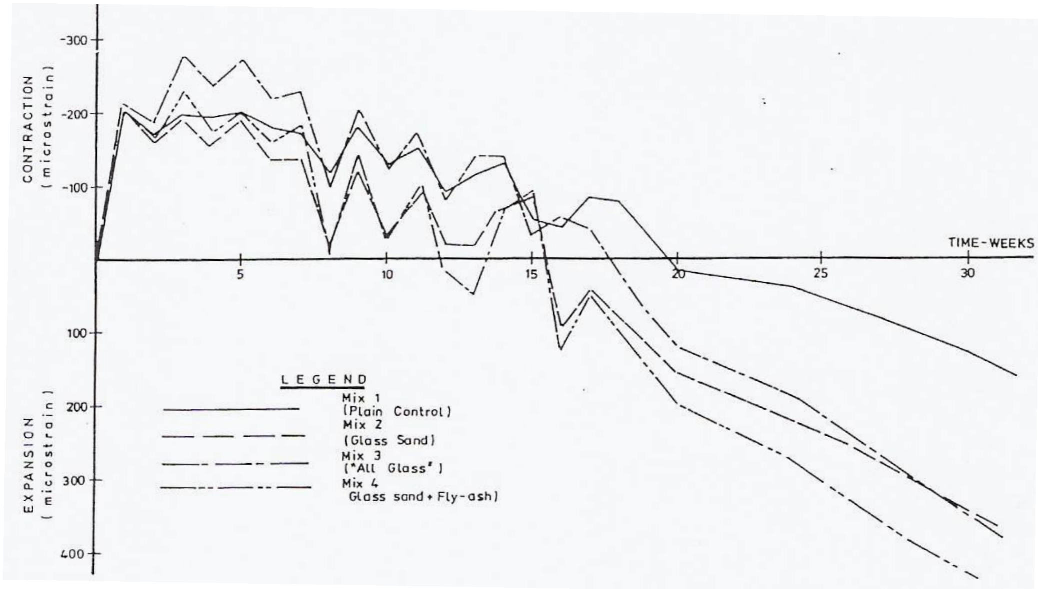

Figure 6 Concrete specimens subjected to cycles of wetting and drying

Concrete mixes containing glass and glass-fly ash exhibited very comparable behaviour. However, under the repetitive cycles of wetting and drying, "plain" control concrete expanded less that the trial mixes, thus reversing the trend evident under the continuous water storage.

CONCLUSIONS AND RECOMMENDATIONS

Evaluating the results of CSIRO and the University of NSW research, one must conclude that soda-lime glass aggregate has the potential for use in structural and durable concretes. The usual requirements of optimum grading, particle shape and cleanliness of aggregate must obviously apply. However, some additional specifications for the selection of mix proportions and ingredients must be made, Samarin [1988]. It is apparent, that soda-lime glass exhibits pozzolanic properties, but these are more evident in particles of very small size. Formation of expansive gel on the surface of glass, as a result of reaction with alkalis, cases distress when the concentration of this gel is high in a particular location within concrete. The smaller is the size of glass particle, the less destructive is the formation and expansion of gel, due to the minute volume that can be produced. Very small glass particles behave no different from pozzolans which are usually included in concrete as very fine powders. If used in conjunction with large glass aggregate particles, pulverized glass or pozzolana react with the alkalis, "mopping them up" before the alkalis can react with the coarse glass aggregate, causing the formation and expansion of gel. Again, it must be emphasized, that it is essential to evaluate local materials in the laboratory tests, before using glass aggregate in structural concrete.

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