Recycled Glass Cullet as Fine Aggregate and Partial Cement Replacement in Concrete

S B Duraman* and Q Li

1 Civil Engineering Programmes, Faculty of Engineering, Universiti Teknologi Brunei BE 1410, Brunei Darussalam
2 State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan Hubei 430070, China
*Corresponding author: saiful.duraman@utb.edu.bn

Abstract. Utilisation of recycled glass cullet in concrete has obvious benefits with respect to environmental conservation and sustainable development. The problems of rising landfills can be reduced. Reduction of primary aggregates for concrete where alternative materials would suffice can also be fulfilled. Glass also contains large amounts of silicon and calcium which means that in theory, is pozzolanic. However, the possibility of alkali-silica reaction (ASR) due to the presence of silica must also be addressed. Tests were performed to investigate the suitability of using cullet in concrete. A sieve analysis was performed to determine the size distribution of the cullet and provided basis to the range of samples that could be cast. Using cullet as partial replacement aggregate in concrete has resulted in minor increases in concrete consistence (workability) and minor reductions in compressive strength. When ground glass cullet (GGC) was used as 30% partial cement replacement, the consistence increased considerably, whilst the later age compressive strength was close or higher (depending on the mix proportions used) compared to the corresponding control mixes, which did not have GGC incorporation. The early age strength was lower and strength development was slower at early ages further suggesting likelihood of pozzolanic activity. Accelerated ASR tests have shown the occurrence of ASR in concrete mixes using cullet as replacement aggregate to be more than control mixes which used conventional aggregate. The magnitude of ASR was also found to be colour dependant- green coloured cullet resulted in less expansion than when using amber cullet. Qualitative microstructural analysis of specimen micrographs recorded in Secondary Electron Imaging (SEI) mode using a Scanning Electron Microscope (SEM) have shown that mortar specimens using cullet displayed more cracking at longer curing periods. Cracks propagated from, and surrounded the glass particles, further suggesting the occurrence of ASR activity. Depending on size classification used, glass cullet can therefore be recommended to be used as partial aggregate replacement and partial cement replacement in concrete. The possibility of durability attack due to ASR reaction must however be taken into consideration.

1. Introduction
In the current period of environmental awareness and sustainable development, the Construction Industry is under pressure to participate actively and this includes increasing usage of reclaimed or recycled materials. By substituting primary materials such as aggregates in concrete with reclaimed or recycled materials, sustainability of construction can be improved. This leads to a reduction in reliance of primary materials and possibly reducing volumes of construction and demolition waste. In addition, this may also lead to utilisation and subsequent reduction of wastes from other industries.
Government Authorities and Organisations have made it necessary for the Construction Industry to use primary aggregates as efficiently as possible. In many countries, taxes have now been imposed, further making the use of reclaimed or recycled materials become more attractive. Alternative materials for aggregates and cementitious materials include demolished concrete, plastics, rubber tyres, bricks, coal production waste, blast furnace waste, and glass. Glass presents good potential since it is commonly segregated during disposal. Even in countries where recycling is in development stages such as Brunei Darussalam, it is common to find dedicated waste-bins for glass waste. Types of glass which may be used includes pyrex glass, window glass, windshield glass, and soda bottles [1].

Using the United Kingdom (UK) as an example, 2.399 million tonnes of glass were disposed in 2017 [2]. As a comparison, the amount disposed back in 1997 was 0.425 million tonnes of glass [3]. More recently however, the brewing industry has started the process of organised retrieval of non-returnable glass initially going to the landfill. From the 2.399 million tonnes of glass disposed in 2017, a comparatively high amount of 1.623 million tonnes, or 67.6% originally disposed, have been recovered and recycled. This success story of glass cullet recycling however, has also had an unforeseen side-effect- the recovery of the green glass has exceeded the quantity of green glass being reproduced, leading to the rise of a green glass ‘mountain’ [4]. From the 2017 figure stated would mean that approximately 32.3%, or 0.776 million tonnes remain unutilised. Alternative uses for the glass recovered therefore need to be considered.

Obvious alternative uses would therefore be the Construction Industry, where utilisation of alternative materials need to be exploited. Cullet has the potential to be used as construction aggregates in addition to being already used as decorative effects. Furthermore, glass is amorphous (crystalline) and contains significant quantities of silicon and calcium which means that in theory, it is pozzolanic [4].

One possible drawback to using glass in concrete however is the possibility of alkali-silica reaction (ASR) occurring because of the known presence of silica in the glass. ASR is the reaction between siliceous presence in (usually) the aggregate and the alkalis (potassium and sodium hydroxide), produced during Portland cement hydration. A gelatinous product is formed which subsequently absorbs pore fluid and in doing so expands, thus creating internal stresses within the concrete. This gel formation will lead to potential damage of the concrete when the 3 factors as follows are present simultaneously in the concrete:

1. Reactive silica is present at a critical amount in the aggregate;
2. Potassium, sodium and hydroxyl ions are present in the pore solution inside the concrete; and
3. Presence of adequate moisture.

This article summarises a study with respect to the potential utilisation of glass cullet in concrete. Accelerated ASR tests were performed using cullet of varying size ranges and colours and were compared against control mixes which used conventional aggregates. Consistence (i.e. workability) and compressive strength development tests were performed both for cullet as replacement aggregate and ground glass cullet (GGC) as partial cement replacement. These were compared against their corresponding control mixes which did not use alternative aggregates or partial cement replacement materials. To further reinforce the findings, qualitative microstructural analysis were done for mortar specimens using cullet as replacement aggregate via Secondary Electron Imaging (SEI) micrographs recorded using a Scanning Electron Microscope (SEM).

2. Experimental Details

2.1. Materials used

Glass cullet samples of varying sizes and colour were obtained from various glass recycling and cement replacement companies. The cullet was purposely left in as-is condition i.e. not rewashed for the study and its quality was therefore dependant upon the washing methods employed by the recycling companies. A particle size distribution (sieve analysis) was initially performed on the cullet samples available. This provided basis to the most optimum range of tests and number of specimens which could be cast for all potential tests discussed in this article. Glass cullet in ground form, referred
in this article as ground glass cullet (GGC), was produced by grinding the glass cullet into powdered form into several size designations. This article discusses the results of mixes utilising GGC of fineness 450 m$^2$/kg, which is found to be representative of the properties of concrete utilising GGC; the results of other fineness will be discussed separately.

Ordinary Portland Cement (OPC) of alkali equivalent 0.68% and specific gravity 3.15 was used as the main cement binder for all mixes. The coarse aggregate (CA) used was 10mm nominal size uncrushed fluvial dragged gravel of specific gravity 2.60. The fine aggregate (FA) used was of similar origins and obtained from the same quarry and has a classification of 62.4% passing a 600µm sieve. Clean, potable, cold tap water was used throughout. Where required, more especially for the ASR and microstructure tests, deionised water was used.

2.2. Summary of mixes used

The results from 6 batch mixes were utilised and discussed in this article. The mixes can be divided into 2 sets, in accordance to the method of mix design proportions used, namely the ASR Mix Set and the DoE Mix Set. The first set utilised the same mix proportions as for the ASR Test (as explained in Section 2.4). Alkali, which was required for the ASR Test, was also added for consistency purposes. The second set was designed using the DoE (Department of Environment) Mix Design Method with mix proportions used designed for 35MPa at 28 day age. Each mix set comprised of 3 mixes- namely the Control Mix, the Glass Mix and the GGC Mix. A brief description of these mixes, and their coding designations is summarised in Table 1.

| Mix Name    | Group Mix Set | Mix Design Method or Mix Proportions Used | Description                                      |
|-------------|---------------|------------------------------------------|-------------------------------------------------|
| ASR Control | ASR           | ASR Mix Proportions                      | Control Mix for ASR Mix Set with normal fine aggregate and 100% OPC |
| ASR Glass   | ASR           | ASR Mix Proportions                      | Cullet used as replacement fine aggregate         |
| ASR GGC     | ASR           | ASR Mix Proportions                      | 450m$^2$/kg GGC used as 30% partial cement replacement |
| DoE Control | DoE           | DoE Mix Design Method                    | Control Mix for DoE Mix Set with normal fine aggregate and 100% OPC |
| DoE Glass   | DoE           | DoE Mix Design Method                    | Cullet used as replacement fine aggregate         |
| DoE GGC     | DoE           | DoE Mix Design Method                    | 450m$^2$/kg GGC used as 30% partial cement replacement |

2.3. Consistence and compressive strength tests

Concrete consistence (workability) was determined using the Slump Test, as per BS EN 12350-2:2009 [5]. Compressive strengths were determined using 100mm dimension cube specimens. A minimum of 3 specimens were used to determine the mean compressive strength of a mix at a particular age. Cube size and number of specimens used to determine were similar to that used by Duraman [6-7], with preference given to 100 mm cubes due to optimal utilisation in laboratory works. The number of specimens used for a mix at a particular age provided a statistically good representation of the mean concrete compressive strength at that age. Abdullah [8] highlighted the differences between specimens of different sizes and hence results from other cube sizes are not discussed here. The compressive strength test procedure used was as recommended by BS EN 12390-3:2002 [9], using a compression testing machine conforming to BS EN 12390-4:2000 [10].
2.4. Alkali Silica Reaction (ASR) tests
The mix proportions used for the ASR Test were as per recommended by BS 812-123(1999):1999 [11], with the exception of 20-10mm aggregates being substituted with 10-5mm aggregates since smaller sized prisms were used. Alkali was also incorporated as per required in the standards.

The test methods used were as recommended by BS 812-123(1999): 1999 [11]. Exceptions included 75*75*250 mm prisms being substituted with 40*40*160 mm prisms due to limitation of cullet available in the required sizes. Due to time limitations, the 38±2°C temperature at which the specimens were recommended to be immersed in after 7 day age was increased to 60±2°C to further accelerate the reaction rate. This temperature deviation was confirmed to have no side-effects to the concrete aside from increasing the rate of reaction. Measurement of expansion due to heat was eliminated by allowing the specimens to reclimatise back to room temperature before measuring their expansions.

The cullet was separated into specific sizes and 3 (or 2 depending on cullet availability) specimens were cast for each sample mix using cullet as replacement fine aggregate. This was compared against a control mix which used normal fine aggregate (FA). The range of cullet size and colour designation used for each sample mix was dependant on cullet availability and is summarised in Table 2.

| Mix Code | CULLET/FINE AGGREGATE USED |
|----------|----------------------------|
| C1       | Control Mix- Normal FA     |
| G1       | Green >5mm                 |
| G2       | Green 3.35-5.00mm          |
| G3       | Green 2.00-3.35mm          |
| G4       | Green 1.18-2.00mm          |
| G5       | Green 600µm-1.18mm         |
| G6       | Green 425-600µm            |
| A1       | Amber 1.18-2.00mm          |
| A2       | Amber 600µm-1.18mm         |

2.5. Microstructural qualitative analysis
Mortar specimens were cast with cullet as replacement FA using mix proportions of 1:0.4:0.3 (Water:Cement:FA). The specimens were water-cured at 20°C at different curing periods. After the required curing period, the specimens were cut into 25mm cube specimens, to expose the internal cross-sectional faces. The specimens were then resin impregnated, ground, polished and coated with a thin layer of carbon, as preparation for microstructural analysis. Micrographs were then recorded in Secondary Electron Imaging (SEI) mode using a Scanning Electron Microscope (SEM) and hence qualitatively analysed.

3. Results and Discussion
3.1. Concrete consistence results
The results of the slump test for the ASR and DoE mix sets are shown in Table 3 and Table 4 respectively, and graphically shown in Figure 1. The concrete consistence (i.e. workability) of the ASR Glass Mix was slightly higher than the consistence for the corresponding ASR Control Mix. However, the consistence of the ASR GGC Mix had increased significantly compared to ASR Control
Mix. The DoE mixes exhibited similar relationships and hence it can be concluded that this trend is consistent regardless of mix design proportions used.

**Table 3. Slump Test Results for ASR Mix Sets**

| Mix         | Slump (mm) |
|-------------|------------|
| ASR Control | 40         |
| ASR Glass   | 55         |
| ASR GGC     | 100        |

**Table 4. Slump Test Results for DoE Mix Sets**

| Mix         | Slump (mm) |
|-------------|------------|
| DoE Control | 20         |
| DoE Glass   | 30         |
| DoE GGC     | 60         |

**Figure 1. Slump Test Results for ASR and DoE Mix Sets**

The reason for the mix using cullet as fine aggregate having higher consistence than the corresponding control mix can likely be attributed to its glassy surface, which would provide less resistance within the fresh concrete. Glass as replacement aggregate would therefore have the added advantage of an increase in consistence. At the same time however, the question of the magnitude of bond between the glass and the cement matrix which would have effect on the hardened properties, especially compressive strength, should also be addressed. These are discussed later.

With GGC used as partial cement replacement, the consistence had increased considerably, however still remained cohesive. It is more than likely that the reason is similar to when using pulverised fuel ash (PFA) as partial cement replacement. The spherical shapes of the PFA particles led to reduced resistance and subsequently consistence increase, as per various studies utilising PFA, including Duraman [7] and Zainassalehen et al [12] who observed increased consistence when incorporating PFA. The cohesiveness property observed may possibly be due to better dispersion of the cementitious particles and also due to the glass particles of the GGC absorbing negligible water during mixing.

3.2. **Compressive strength test results**

The compressive strengths at specified ages for the ASR and DoE mixes are graphically shown in Figure 2 and Figure 3.
Both the DoE and ASR Mix sets showed that cullet used as replacement fine aggregate gave lower strengths compared to their respective control mixes. This is as expected, as the fine aggregate contributes to the overall strength of the concrete, and the cullet is of lower compressive strength than the sand. In addition, the glassy surface nature of the cullet which had been mentioned previously to improve consistence has likely contributed also to this lower compressive strength due to a reduction in bond between the cement and the cullet fine aggregate.

The ASR Glass Mix was closer to its corresponding control mix in comparison with the DoE Glass mix to its control mix. The reason can be attributed to replacement of sand with cullet at equal weights. With the DoE Glass Mix, replacement was done taking into consideration percentage passing through a 600µm sieve as per DoE Method of Mix Design. The cullet used was coarser than sand, this corresponded to lower percentage passing and hence more cullet was used as per mix design methodology (and similarly less normal CA was used). This further justifies the previous statement that cullet is of lower strength than sand. The required target compressive strength can readily be achieved with a more detailed study to obtain a more optimal mix design, by taking into consideration the lower compressive strength of cullet as compared to normal fine aggregate during the mix design process.

When GGC was used as 30% partial cement replacement for both the DoE and ASR Mix sets, the strength development was initially lower and increased only after 1 week. In contrast, both the DOE and ASR Control mixes underwent more strength development during the first 3 days. The later age strengths of the cement replacement mixes were however comparable to their corresponding control mixes. The results suggest the likelihood of pozzolanic activity from the GGC. Strength development is slower because the GGC requires calcium hydroxide (CH) which is produced from the cement hydration, for activation of the GGC to occur. This in-turn also indicates that the microstructure of the concrete is denser by using GGC, as the CH produced as a by-product of the C-S-H evolution would have been consumed by the pozzolanic reaction of the GGC.

The ASR GGC Mix compressive strength at later age is closer in value with the ASR Control Mix as compared to the DoE GGC Mix with the DoE Control Mix and is highly likely due to the inclusion of the alkalis. It is recapped that alkali had been included although the main purpose was for consistency with the specimens for ASR Tests. This alkali inclusion may likely have had the effect of...
increasing the rate of hydration reaction of the GGC via alkali activation. Subsequently, more tests are recommended to further confirm this, including concrete mixes using the ASR mix proportions, though without alkali inclusion.

3.3. Alkali Silica Reaction (ASR) test results

The percentage expansion due to ASR for each specimen was determined at various ages. For each specimen at each age, 4 readings were taken and the mean used to represent the specimen at that age. The readings were confirmed to be statistically consistent. Figure 4 shows the mean expansion for each specimen at each age. Figure 5 and Figure 6 shows the mean percentage expansion according to size classification for the green cullet and amber cullet respectively. Figure 4 shows that ASR expansion occurs for all of the specimens under the accelerated ASR test conditions.

Figure 5 and Figure 6 shows that for the same size designation, the specimens using amber cullet undergoes either the same expansion, or more expansion due to ASR than the specimens using green cullet. Overall, the magnitude of expansion due to ASR was greater for the amber cullet specimens than the green cullet specimens, with 0.195% at 36 days compared with 0.144% at 38 days for the amber cullet and green cullet specimens respectively. This compares well with Tan and Du [13] who found expansion with amber cullet to be more than with green cullet at similar 100% replacement levels. Meyer and Xi [1] and Jin et al [14] found amber and clear cullet to be most reactive compared with green cullet. Dhir et al [15] and Byars [16] found equal expansion with both amber and green cullet. Dhir et al [15] further added though that both colours were greater than with using clear cullet.

The actual chemical compositions of the specimens used were not available nor determined, but however for comparison purposes, Table 5 shows the chemical composition for amber and green cullet [1,14,17]. Both the alkali and silica are seen to be higher in magnitude in the specimens using amber cullet than with green cullet; however these differences are comparatively minor. They proposed that the presence of the chromium compound, which is required to obtain the specific green colour may act as a suppressant to ASR. At the same time, Dhir et al [18] summarised the chemical composition based on statistical mean percentage and showed the range of chemical compositions found. The mean results were various cullet samples (termed soda lime bottles) from various cullet samples (termed soda lime bottles) from various countries.

For the results of this study, it can therefore be concluded that this the differences in expansions when using cullet of different colours is most likely due to the additions used to obtain that colour for the cullet. Specifically, for the green cullet is likely due to the addition of chromium used to obtain the green colour. The similarities or differences in relationships with the other studies is most likely due to similar or differing chemical compositions of the cullet used in the studies. It is also highlighted that since the cullet used was a waste product itself, and has originated from different sources of glass manufacturers.

| Table 5. Chemical Compositions of Amber and Green Cullet (unit %) [1,14,17] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | SiO₂            | Al₂O₃           | Na₂O + K₂O      | CaO + MgO       | SO₃             | Fe₂O₃           | Cr₂O₃           |
| Amber Cullet   | 71.9 to 72.4    | 1.7 to 1.8      | 13.8 to 14.4    | 11.6            | 0.12 to 0.14    | 0.30            | 0.01            |
| Green Cullet   | 71.27           | 2.22            | 13.06           | 12.17           | 0.052           | 0.599           | 0.43            |
Figure 4. Mean ASR Expansion of Each Sample Mix Based on Age in Days

Figure 5. Mean ASR Expansion of Specimens Using Green Cullet Based on Size

Figure 6. Mean ASR Expansion of Specimens Using Amber Cullet Based on Size

The maximum peak for green cullet in Figure 5 suggests the ‘pessimum’ size to be 2–3.35mm. This is comparable to proposals by Meyer & Xi [1] who suggested the pessimum size of cullet to be about
0.60 mm to 1.18 mm. This is an acceptable comparison with the results obtained with the differences possibly due to the different chemical compositions of the cullet used. Several authors give various interpretations of pessimum size. Dyer & Dhir [4] suggested that pozzolanic and ASR were similar, with the pessimum being the region where the pozzolanic reaction starts to become more predominant. This pessimum size consideration also raises the question whether if ground fine enough such that the cullet becomes pozzolanic, would in effect eliminate the ASR effect.

For the amber cullet, it was found that using 1.18 mm to 2.00 mm cullet size underwent more expansion than 0.60 mm to 1.18 mm. No pessimum size is however proposed for the amber cullet since the range of size designations used during the study were too few, due to lack of availability. However, it can be similarly concluded that ASR magnitude is size dependant, as per the findings made when using green cullet. Further tests using more size designations are therefore recommended.

No expansion limits were quoted in the procedure for the ASR Test. However, from similar tests, Swami [19] suggested that 0.04% expansion after approximately 1 year is considered as a reasonable number to separate potentially deleterious reactive aggregates from aggregates which are not reactive. It is re-highlighted that the tests for this study had been modified in order to accelerate the reaction process due to time constraints during the study. The most significant factor was the increase in temperature which had increased the rate of reaction. However, the comparison of expansions between the specimens used would still hold, since all were subjected to similar conditions. With this respect, Figure 4 confirms that all of the specimens using cullet as fine aggregate had undergone more expansion compared to the control specimens which had nil cullet inclusion. The sample containing cullet undergoing the least expansion was that using green cullet of size range 425-600µm (G6) with 0.041% at 38 days, compared to the control with 0.028% at 32 days.

3.4. Microstructural qualitative analysis results

Figure 7 and Figure 8 show SEM micrographs taken at similar 200x magnifications for 10 day and 100 day cured specimens. Comparing specimens of similar sample mixes at curing periods of 10 day age and 100 day age showed that cracks were more predominant for those specimens cured to 100 day ages. At higher magnifications, cracks were clearly shown and are circumferential to the glass particles. In addition, cracks in the cement paste propagated from the glass particles. It is highly likely that these cracks were due to occurrence of ASR.

Furthermore, the qualitative analysis of the SEM micrographs also reinforce the previous assumptions made with respect to the increase in consistence and decrease in compressive strength when using cullet as replacement fine aggregate i.e. due to the glassy surface.
4. Conclusions
Using cullet as replacement fine aggregate has resulted in slight increases in concrete consistence and decrease in compressive strengths. Using ground glass cullet (GGC) as replacement pozzolan has resulted in significant increases in consistence, lower early compressive strengths and comparable later age strengths. The consistence increase of the former was attributed to the glassy surface of the cullet, and this assumption was reinforced from the qualitative microstructural analysis. The consistence increase of the latter was attributed to better dispersion of the GGC particles. The lower early compressive strengths but comparable later age strengths reinforce the occurrence of pozzolanic activity of the GGC particles. Similarly, this assumption was reinforced from the microstructural analysis. These findings were consistent regardless of the concrete mix proportions used, thus further reinforcing the conclusions made. The lower compressive strength when using cullet as replacement fine aggregate can readily be overcome with improved mix design of the concrete components.

Alkali Silica Reaction (ASR) tests have shown that under accelerated conditions, ASR activity occurred more in specimens using cullet as replacement fine aggregate in comparison to mixes which used conventional fine aggregate. Furthermore, the magnitude of ASR expansion was found to be both colour and size dependant. Amber cullet exhibited more ASR than green cullet. The difference due to colour was attributed to be due to the chemical(s) and/or compound(s) used to obtain that colour, in the case for the green cullet was due to chromium. The pessimum size for green cullet was found to be between the range 2 to 3.35mm size. Microstructural analysis have confirmed ASR activity occurring at later ages. Similarly, cracking was shown in the microstructural analysis and is attributed to be ASR.

It can further be concluded that depending on the size classification, glass cullet can be used as partial replacement aggregate and/or as partial cement replacement in concrete. However, the possibility of durability attack due to ASR must be taken into consideration. The significance of size and magnitude of ASR with respect to pozzolanic activity was also raised. Further tests are recommended using more size designations which would measure both the engineering and durability properties of concrete incorporating recycled glass cullet leading to further understanding of the effect of different sizes of GGC.

5. References

[1] Meyer C and Xi Y 1999 Use of Recycled Glass and Fly Ash for Precast Concrete, *Journal of Materials in Civil Engineering* **11**(2) 89-90
[2] Department for Environment Food & Rural Affairs 2015 UK Statistics on Waste retrieved on July 1, 2020 from http://www.gov.uk/government/uploads
[3] Guthrie P, Coventry S and Hillier S 1999 *The Reclaimed and Recycled Construction Materials Handbook* CIRIA Publication 513, 1st Edition.
[4] Dyer T D and Dhir R K 2001 Chemical Reactions of Glass Cullet Used As Cement Component, *Journal of Materials in Civil Engineering* **13** 412-417
[5] BS EN 12350-2:2009 *Testing fresh concrete. Slump-test* (British Standard Institution).
[6] Duraman S B 2018 Properties of Neat and Blended Concrete Systems Exposed to Standard 20°C and Elevated 38°C Temperature Conditions, *IOP Conf.: Mater Sci Eng.* **431** 052002
[7] Duraman S B and Richardson I G 2020 Microstructure & properties of steel-reinforced concrete incorporating Portland cement and ground granulated blast furnace slag hydrated at 20 °C, *Cement and Concrete Research* **137** 106193
[8] Abdullah A 2020 Effects of specimen sizes and loading rates on compressive strength of concrete, *Materials Today: Proceedings* ISSN 2214-7853
[9] BS EN 12390-3:2002 *Testing Hardened Concrete. Compressive Strength of Test Specimens* (London: British Standard Institution).
[10] BS EN 12390-4:2000 *Testing Hardened Concrete. Compressive Strength. Specification for Testing Machines* (London: British Standard Institution).
[11] BS 812-123(1999): 1999: Testing Aggregates - Part 123: Method for Determination of Alkali-Silica Reactivity - Concrete Prism Method (London: British Standard Institution).

[12] Zainasallehen S S H and Duraman S B 2018 Properties of PFA Concrete at Different Curing and Exposure Conditions in Hot Weather Environment, *IOP Conf.: Mater Sci Eng.* 431 052007

[13] Tan K H and Du H 2013 Use of waste glass as sand in mortar: Part I – Fresh, mechanical and durability properties, *Cement and Concrete Composites* 35(1) 109-117

[14] Jin W, Meyer C and Baxter S 2000 ‘Glasscrete’ – concrete with glass aggregate, *ACI Materials Journal* 97(2) 208–213

[15] Dhir R K, Dyer T D and Tang M C 2009 Alkali-silica reaction in concrete containing glass, *Materials and Structures/Materiaux et Constructions* 42(10) 1451-1462

[16] Byars E A, Morales B and Zhu H Y 2004 Conglasscrete I (Project Code: GLA2-006) *The Waste and Resources Action Programme, Oxon, UK* pp 54

[17] Guo P, Meng W, Nassif H, Gou H and Bao, Y 2020 New perspectives on recycling waste glass in manufacturing concrete for sustainable civil infrastructure, *Constr. Build. Mater.* 257 119579.

[18] Dhir R K, de Brito J, Ghataora G S and Lye C Q 2018 Production and Properties of Glass Cullet Sustainable Construction Materials (Woodhead Publishing Series in Civil and Structural Engineering, Woodhead Publishing) chapter 3 pp 35-96

[19] Swamy R N 1992 Testing for alkali-silica reaction Swamy *Alkali-silica Reaction in Concrete* ed (Blackie and Son Ltd) chapter 3