Int. Journal for Housing Science, Vol.35, No.2 pp. 69-80, 2011
Published in the United States

SUSTAINABLE CONCRETE ROOF TILES CONTAINING RECYCLED GLASS

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ABSTRACT

The final disposal route of post-consumer recycled glass (RG) is a common issue for many municipalities worldwide. Approximately 1 million tons of glassware is produced per year in Brazil, only 47% of which are currently recycled. The idea of incorporating RG as aggregate for concrete emerged in the 60´s motivated by some of the advantages of glass, i.e. low water absorption, high abrasion and durability, aesthetic potential among others. However, the initial researches have shown that concretes containing RG exhibited marked strength regression and excessive expansion due to alkali-aggregate reaction (ASR), which limited further research. The topic emerged again in the 90´s, imposed by the sustainability issues. Moreover, new studies aimed to determine the conditions at which ASR does not occur, as well as the influence of RG on the physical properties of concrete. Despite some literature on the use of RG into concrete, its application for making concrete roof tiles is still not documented. The incorporation of RG into those products, if feasible, may create a sustainable material for construction by reducing the land-filling of RG in

0146-6518/02/69-80, 2011

municipalities near the concrete tile plants. This paper investigates the use RG as replacement of 7.5% and 15% silica aggregate in concrete roof tiles. Three grading of RG were studied, i.e. particles retained between 4.76 – 1.68 mm, 1.68 – 0.84 mm and 0.84 – 0.30 mm sieves. Metakaolin (MK) has been chosen to replace 7.5% and 15% wt. cement and potentially suppress ASR. The physical properties assessed were dry bulk density, compressive strength and modulus of elasticity; the engineering properties determined were apparent porosity and oxygen permeability. Results showed that the use of 7.5% RG in combination with 7.5% MK provided equivalent performance to reference semi-dry pre-cast concrete and, therefore, permit a new route of disposal for the RG.

Key words: Recycled Glass, Sustainability, Concrete Durability

Introduction

The disposal of recycled glass (RG) is a common issue for many municipalities worldwide, although glass is potentially a 100% recyclable material when melted and reused for glass manufacture. The glass industry rejects RG because it is a mixture of several types of glasses with different composition; therefore it is often treated as a contaminated material [1].

The idea of the incorporation of RG as aggregate for concrete emerged in the 60´s and 70´s [2,3], motivated by some of the advantages of this material [4,5] e.g. extremely low water absorption; high durability of the glass particles; higher abrasion resistance of concrete; improvement of the flow properties of fresh concrete; aesthetic potential etc. The early work [2,3], however, has proved that concretes containing RG exhibited marked strength regression and excessive expansion due to alkali-silica reaction (ASR) and much of the research has been abandoned. This topic emerged again at the end of the 90´s [6], as a result of the sustainability drive. Much of the recent studies have been carried out at Columbia University (New York) [4,7] and in the UK [8,9].

Those studies aimed to determine the conditions at which ASR does not occur, as well as the influence of RG on the physical properties of concrete. However, there is still no agreement on the optimum amount of RG to be used in concrete. Some authors [4,5] define 10% replacement as optimum limit to keep favourable properties in the fresh and hard states; others [10,11] have found that 20% RG gives satisfactory results as substitute for natural fine aggregate or that 25% replacement of aggregate gives low risk of ASR in concrete blocks without cement replacement [12]. In general, it is well accepted [7,8] that ASR can be suppressed by: (i) using low alkali cements; (ii) replacing PC with mineral admixtures, e.g. 20% metakaolin (MK), 30% pulverized fly ash (PFA) or 40% ground granulated blast furnace slag (GGBS); or (iii) grinding glass below 0.3 mm according to [7] or below 1.0 mm as per [8]; (iv) sealing the concrete to prevent moisture ingress.

This paper aims to develop sustainable concrete tiles containing recycled glass. So far, the high availability of building materials as well as the low cost of disposal through landfill has somehow limited the demand and use of RG as a construction material in Brazil [10]. The market of concrete tiles in Brazil is still low, restricted to upper class construction, but has been increasing every year. The price of the product when compared with ceramic tiles is the main barrier to market growth. The incorporation of RG into those products, if feasible, may (i) reduce costs allowing for a market growth; (ii) create a "green label" for those products contributing to a sustainable construction; (iii) ultimately reduce the land-filling of RG in municipalities near concrete tile plants.

The physical properties of semi dry concrete mixes (typically used for concrete roof tiles) incorporating RG as replacement of silica sand were determined. MK was also used to potentially mitigate ASR and this together with the development of the microstructure and susceptibility of these concretes to ASR will be published in due course.

Materials and Methods

Raw Materials

A Brazilian CP-V ARI rapid-hardening cement (PC) [13] was used as binder and supplied by Holcim Brazil. Metakaolin (MK), supplied by Metacaulim do Brasil Company, was used as PC replacement and the quartz aggregate was supplied by Moinhos Gerais Company. The quartz aggregate was sieved and the particle size distribution (PSD) was constructed as described the common range used for production of concrete roof tiles. A constant PSD of the aggregate avoids the difference in particle packing among the concretes studied and keeps the same rheology for all experimental conditions.

A local recycling plant in São João del Rei city, Minas Gerais, Brazil supplied the RG. The bottles were washed, ground and classified by sieving using US-TYLER mesh scale. RG replaced 7.5% and 15% quartz aggregate in some mixes. Whenever RG was added, the corresponding mass percentage of quartz aggregate with the same grading was removed from the recipe; so the overall PSD of the aggregates was also constant when the RG was incorporated.

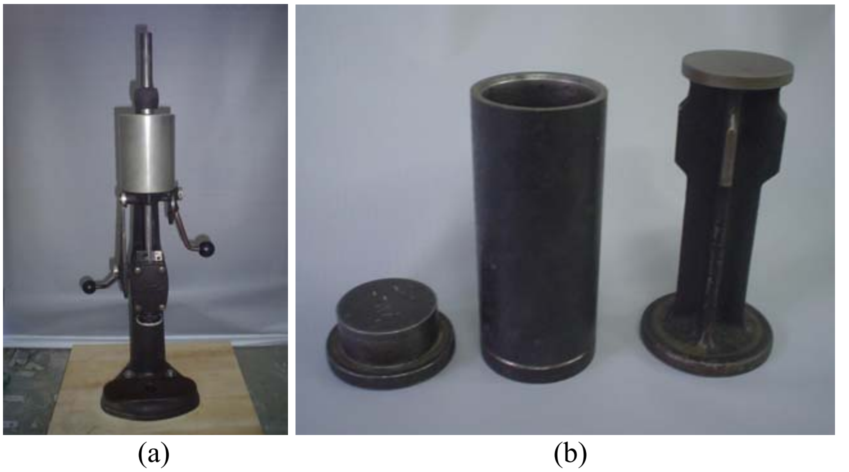
Full Factorial Design

The statistical method of Design of Experiment (DOE) and the Analysis of Variance (ANOVA) provides the significance of each experimental factor on the responses. The following responses were investigated in the experiment: bulk density; compressive strength; modulus of elasticity; apparent porosity and oxygen permeability. Three experimental factors were chosen: particle size of RG (4-10 US Tyler, 10-20 US Tyler, 20-50 US Tyler); fraction of RG (0%, 7.5% and 15%); and fraction of MK (0%, 7.5% and 15%).

Mixing, Casting and Curing

The semi-dry concrete batches were mixed in a Hobart mixer, according to the procedure established by the BS EN 12390-2 [14]. The water to cement ratio and binder to aggregate ratio were kept constant at 0.42 and 0.28, respectively, for all mixes. The concrete samples were cylinders produced by compaction with a hammer, which reproduces in the lab the compaction to which concrete is subjected when extruded to produce roof tiles (Fig. 1). In this work, the mass of concrete used was always 215 grams and specimens were always hammed with 25 blows. Cylinders of approximately 48 mm height were produced with the parameters chosen. However, the height was always checked with a calliper. The diameter of the cylinders was set by the steel mould (50 mm).

After de-moulding, the samples were thoroughly wrapped with a plastic film to avoid desiccation and transferred to an oven where they were cured at 50°C for 6 hours to reproduce the thermal curing at a concrete plant. After this short-term curing regime they were subsequently cured at laboratory conditions (20° C and 60±5 R.H.) for 28 days prior to testing.



(a) (b)

Figure 1 : (a) hammer (b) metallic moulds

Experimental

The dry bulk density of the concrete cylinders was calculated by dividing the dry weights (after 24 hours of drying at 105°C) by the bulk volume of the samples. The bulk volume was calculated from the dimensions, approximately 50 mm of diameter and 48 mm of height, using a calliper.

Cylinders of 48 mm height x 50 mm diameter were tested in compressive strength; the modulus of elasticity was carried out based on the recommendations of BS 1881-121 [15]. Five cylinders were tested for each experimental condition and replicate.

The apparent porosity was calculated by the vacuum saturation method according to the RILEM specification CPC 11.3 [16]. Oxygen permeability was carried out using the Leeds permeability meter described by Cabrera and Lynsdale and this method is described elsewhere [17]. The samples used for testing are shown in Figure 2.

Figure 2 : Cylinders after curing

Results and Discussion

Table 1 shows the P-values of Analysis of Variance (ANOVA) for the mean of the responses. The P-values indicate which of the effects in the system are statistically significant. If the P-value is less than or equal to 0.05 the effect is considered significant. The results are presented via 'main effect' and 'interaction' plots. These graphic plots cannot be considered typical 'scatter' plots, but rather illustrate the statistical analysis and provide the variation of the significant effects. The main effect of a factor must be individually interpreted only when there is no evidence of interaction with other factors. When one or more interaction effects of superior order are significant, the factors that interact must be mutually considered [18].

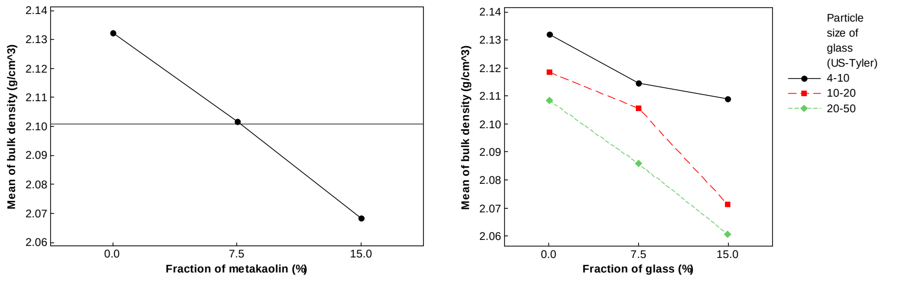
Table 1 : Analyses of variance (ANOVA)

	P-value ≤ 0,05				
Factors	Bulk density	Apparent porosity	Permeability	Compressive strength	Modulus of elasticity
Particle size of RG	0.000	**0.000**	**0.008**	0.000	**0.002**
Fraction of RG	0.000	**0.000**	**0.004**	0.000	**0.000**
Fraction of MK	**0.000**	**0.000**	0.239	0.000	**0.000**
Particle size of RG * Fraction of RG	**0.020**	0.102	0.180	0,346	0.294
Particle size of RG * Fraction of MK	0.999	0.283	0.311	0.389	0.318
Fraction of RG * Fraction of MK	0.819	0.515	0.737	0.213	0.287
Particle size of RG * Fraction of RG * Fraction of MK	0.213	0.152	0.378	**0.007**	0.148
Variance	0.0113	0.5289	0.0000	1.5229	1.7138
R^2 (adj)	94.93%	95.32%	75.50%	83.39%	81.26%

Bulk Density

Overall the bulk density data varied from 2.00 g/cm^3 to 2.19 g/cm^3 for all concretes. The interaction of particle size of RG and fraction of RG was significant exhibiting a P-value of 0.02. As this interaction effect was significant, the corresponding main effects were not analysed separately. The only main factor analysed was fraction of MK (P-value = 0.00). Figures 3a and 3b show, respectively, the main and interaction effect plots for the response bulk density. The increase of MK from 0 to 15% provided a reduction of the bulk density (Fig. 3a), although it was expected the pozzolanic reaction of MK to form more hydrates. The overall decrease in density was probably caused by (i) lower density of MK compared to PC; (ii) lower compaction of concrete when higher amounts (15%) of MK were presented.

Figure 3b shows that the bulk density decreased as the amount of RG increases in the mixes. This is partially explained by the difference in density between glass (~ 2.18 g/cm^3) and quartz (~ 2.65 g/cm^3). Furthermore, the particles of RG were more angular than quartz sand, which may have reduced the effectiveness of compaction when RG was used. Results have also shown that the drop in bulk density is more prominent for finer particles, as shown for those retained between 20-50 US-Tyler (0.84 mm - 0.3mm). These results indicate that either the particle packing is reduced or compaction is less efficient when finer RG is used.



(a) (b)

Figure 3 : Main effect plot (a) and interaction effect plot (b) for bulk density

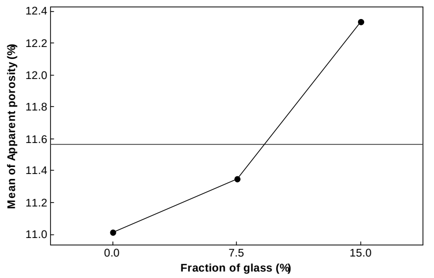
<u>Apparent Porosity</u>

The apparent porosity results varied from 7.87% to 16.44%. The main effects particle size of RG, fraction of RG and fraction of MK were significant. There was no interaction effect on this response (Table 2). The addition of RG to the concrete mixes was responsible for an increase of up to 12% in apparent porosity (Fig. 4a). This is totally in line with the findings of the previous section (bulk density), i.e. that the particle packing or compaction was reduced when RG replaced quartz sand in the mixes.

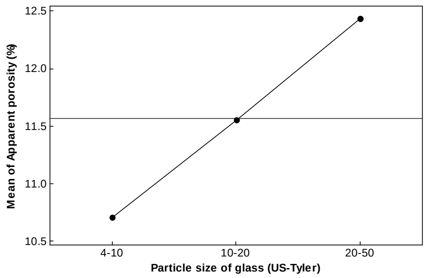
Figure 4b shows the main effect plot of particle size of RG for apparent porosity. It is possible to observe that a reduction in the particle size of RG from 4-10 US-Tyler to 20-50 US-Tyler corresponded to 16% increase in apparent porosity. This result was also in line with bulk density and has shown that finer particles of RG may be detrimental for the physical properties of concrete roof tiles. The fraction of MK significantly affected the apparent porosity of the concretes. Figure 4c shows that the addition of 15% MK was responsible for 34% increase in apparent porosity, compared with the reference mix (i.e. containing no RG and no MK). This behaviour is in accordance to the bulk density results exhibited in Figure 1a, which indicated the reduction of density as a function of the addition of MK.

<u>Oxygen Permeability</u>

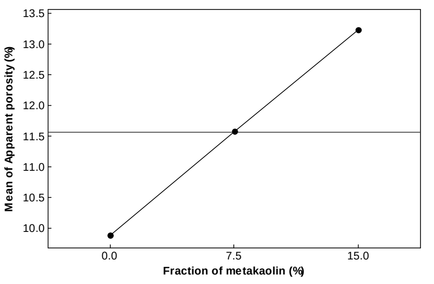
Overall the oxygen permeability data varied from 2.68×10^{-5} m^2 to 2.26×10^{-4} m^2. According to the ANOVA, the main factors particle of RG and fraction of RG significantly affected the response exhibiting the P-values 0.008 and 0.004, respectively. Figures 5a and 5b show the main effect plots for those factors. The rise in permeability caused by the addition of RG (Fig. 5a) is in line with bulk density and apparent porosity results. However, unlike the other responses, the increase in oxygen permeability was extremely high, i.e. 700%, when particles of RG reduced in size from 10-20 to 20-50 US-Tyler in the mixes (Figure 5b). A small variation of the particle size of the aggregate allows for a relevant discrepancy of the permeability results. The permeability results are also in line with previous responses, i.e. bulk density and apparent porosity, regarding to the effect of particle size of RG. However, the oxygen permeability is much more sensitive to changes in RG particle size.



(a)

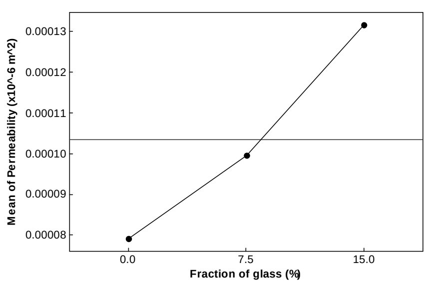


(b)

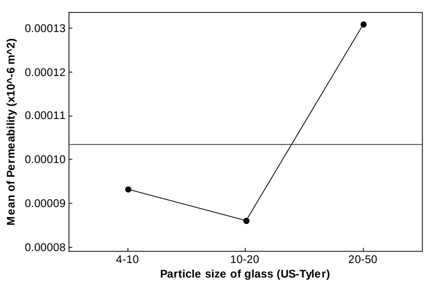


(c)

Figure 4 : Main effect plot for apparent porosity, (a) fraction of RG, (b) particle size of RG, (c) fraction of MK



(a)



(b)

Figure 5 : Main effect plot for oxygen permeability; (a) fraction of RG; (b) particle size of RG

<u>Compressive Strength</u>

The compressive strength data varied from 22.42 MPa to 36.73 MPa. Figure 6a indicates that, irrespective of the particle size of RG, an increase in the fraction of RG reduced the compressive strength of the concretes. However, 7.5% RG has marginal reduction in this response and, therefore, this percentage may be acceptable in terms of mechanical strength. Interestingly, the effect of particle size of RG on the compressive strength is not in line with the other properties discussed so far, as the concretes containing the mid-range PSD of RG (i.e. retained between 10-20 US-Tyler) exhibited the lowest compressive strength results. The addition of 7.5% of MK provided an increase in compressive strength, probably due to the formation of extra C-S-H through pozzolanic reaction; however 15% MK was not satisfactory, exhibiting strength reductions (Fig. 6b). The MK supplier had already indicated that the optimum fraction of that type of MK commonly lies between 7.5-10%. Although 7.5% MK may slightly increase the strength of the concretes (or at least keep it in the same range as the reference mix), this pozzolanic material has shown no significant effect on permeability and detrimental effect on apparent porosity. Results so far indicate that the choice of MK may be conditional to its effect on the mitigation of ASR, which will not be discussed here, but not to enhance the physical and engineering properties. Figure 6c shows that the combination of RG and MK provided suitable compressive strength (i.e. compared to reference) when 7.5% MK and 7.5% RG were used in the mixes.

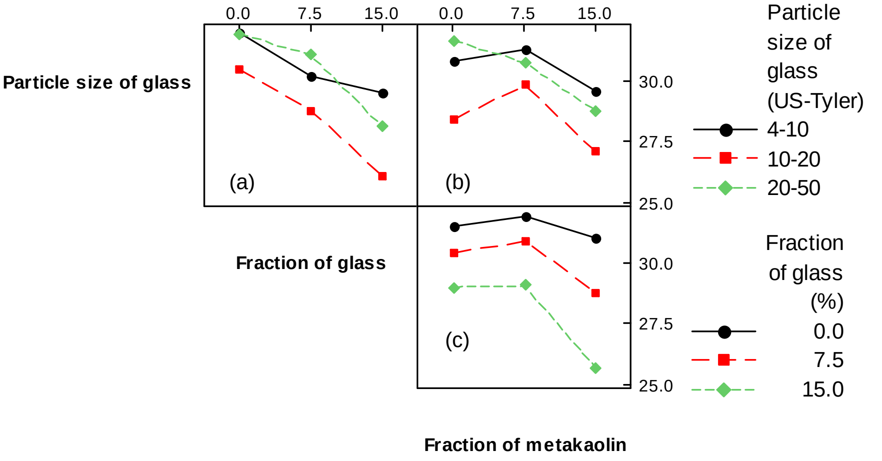
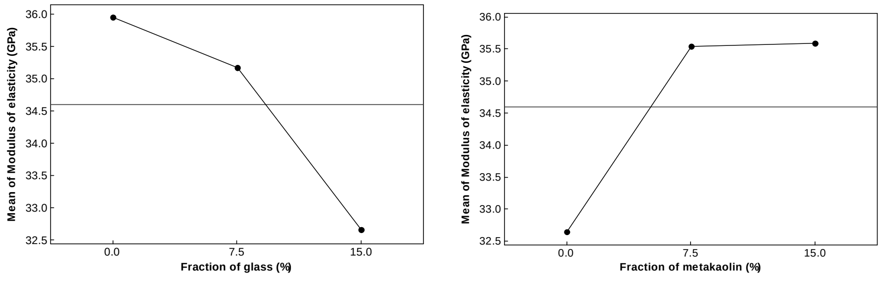


Figure 6 : Interaction effect plot for compressive strength, particle size and fraction of RG and fraction of MK

Modulus of Elasticity

The modulus of elasticity data varied from 28.42 GPa to 39.50 GPa. As observed in Table 1, all main factors exhibited P-values lower than 0.05, thus, significantly affecting the response. The main effect plot for fraction of RG is showed in Figure 7a. A 10% decrease in the modulus of elasticity was observed when the RG addition varied from 0% to 15%. However, the absolute variation is not too significant, i.e. the mean of the modulus of elasticity drops from ~36GPa (reference) to ~32.5 GPa when 15% RG is used. If 7.5% RG is employed, the modulus of elasticity is nearly the same as the reference mix (without RG), which is probably a better option. The addition of MK increased the modulus of elasticity of the concretes (Figure 7b). Although the addition of MK from 7.5 to 15% decreased the compressive strength (Figure 6b and 6c), the same variation is not exhibited for the modulus of elasticity. Moreover, it is possible to say that the experimental level of 7.5% MK is recommended, presenting not only a satisfactory compressive strength but also higher modulus of elasticity.



(a) (b)

Figure 7 : Main effect plot for modulus of elasticity, (a) particle size of glass, (b) fraction of glass, (c) fraction of MK.

Conclusion

RG can be used as replacement of silica sand for the manufacture of concrete roof tiles. In general, the addition of RG has a negative impact on the physical and engineering properties of concrete tiles. However, 7.5% RG gave acceptable results when compared to the reference mix (without RG) and, therefore, could be considered for future investigations. Coarser particles of RG (i.e. retained between 4-10 US Tyler sieves) provided better mechanical behaviour to those concretes than smaller particles (retained between 10-20 and 20-50 US Tyler), i.e. (i) higher bulk density and compressive (ii) lower porosity and permeability.

MK is commonly used to mitigate ASR when RG is used in concrete, although the susceptibility to this reaction has not been tested in this paper. The incorporation of 7.5% MK increased the compressive strength and modulus of elasticity, probably through pozzolanic reaction. However, this percentage of MK was responsible for a decrease in bulk density and rise in apparent porosity. These results indicate that MK should be used only as ASR suppressor, if found effective, rather than pozzolanic material to enhance mechanical and engineering properties. 15% MK should be avoided as the mechanical properties tend to worsen significantly.

In general, the concrete manufactured with 7.5% RG, particle size of RG between 4-10 US Tyler and 7.5% MK provided satisfactory results in terms of mechanical strength. However, the specification of RG for concrete tiles is still conditional to the susceptibility of this material to ASR.

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