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Evaluation of three test methods for determining the alkali–silica reactivity of glass aggregate

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ABSTRACT

Consumption of natural raw materials and pollution have become significant problems due to technological developments and continual increase in demand. Accordingly, great efforts are being made in order to recover wastes including glass. One of the possible applications is utilizing waste glass in concrete; however, alkali–silica reaction (ASR) is of major concern. In this study, tests were conducted by applying three different procedures: ASTM C1293, RILEM AAR-2, and microbar test methods. In microbar testing, glass aggregate was used as coarse aggregate, whereas the other two methods dealt with investigating the reactivity of the finer fraction of the waste glass. The effects of chemical composition, particle size and amount of glass in the mixture were studied. According to the results, flint glass expanded to a greater extent than amber and green glass. Expansions, within the specified time periods dictated by the methods, remained low; however, extended durations resulted in very high length change values of the flint glass-including mixtures, particularly in the AAR-2 and microbar tests.

1. Introduction

Compared to other engineering materials, concrete is the most popular one owing to its availability, excellent resistance to water, its lower cost and the ease with which it can be formed into a variety of shapes and sizes [1]. Due to these primary and also many other advantages for different applications, concrete production figures have reached huge amounts and concrete has become the world's most consumed man-made material [2]. In 2009, approximately 66.4 million m^3 of ready-mixed concrete was used in the construction industry in Turkey. It appears that on a per capita basis, concrete consumption in Turkey has reached 0.93 m^3. 21 Member countries of the European Ready Mixed Concrete Organization including Turkey produced 377.4 million m^3 of concrete in 2009, which corresponds to 0.70 m^3 production per capita [3].

It is evident that the natural resources are rapidly consumed by the industrially advancing world to obtain raw materials for cement and concrete. Sustainable development in concrete production requires reducing the greenhouse gas emissions, energy consumption and raw material resource depletion. Utilizing by-products or wastes as alternative materials in concrete as aggregate or cementitious material will provide a more sustainable concrete technology through the creation of a balance between development and environment [4].

Another global concern about the environment is the increased amount of waste resulting from rapid urbanization and population growth in parallel with technological developments and industrialization. The world is trying to cope with this problem by converting the wastes generated as a result of production, marketing and consumption activities into economic assets. For this purpose, waste management strategies are developed and regulatory programs are established to reach the sustainable development objectives. In Turkey, waste management has been the subject of a number of legal arrangements since the 1930s [5]. In spite of the strict regulations on solid waste management and the efforts to change open waste disposal sites into modern recycling facilities, Turkey still has over 2000 open dumping areas. According to the Turkish State Institute of Statistics figures, in 2008, approximately 52% of the municipal solid waste collected in Turkey was sent to such open dumping areas [6].

It is well known that containers and packaging materials such as glass, metal, paper and plastic are the most common recyclable materials. Among these, glass can be recycled infinitely with no quality loss and glass recycling offers significant benefits from both economic and environmental points of view. By using waste glass cullet as a secondary raw material in the production of new bottles and jars; (i) raw materials are saved, (ii) the energy demand in manufacturing process is dropped, (iii) CO_2 emissions are reduced, and (iv) the furnace life is extended due to the reduced melting temperature [7].

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27 Members of the European Union reached an overall glass recycling rate of 67% in 2009 according to the European Container Glass Federation (FEVE). In Europe, glass recycling statistics varied from one country to another and Belgium was the leading one with a recycling rate of 96%. Austria, Netherlands, Sweden and Switzerland were the other countries that recycled at least 90% of their glass waste in 2009. On the other hand, Greece was the least successful since the glass recycling rate remained at 15% [8]. In Turkey, lack of a well-organized collection system for recoverable wastes, insufficient funding for recycling programs and low societal awareness of sorting recyclables are some reasons which led to glass recycling rate of only 25% in 2009 [6,8].

New glass can be produced from old glass only if the level of contamination from other categories and other colors of glass, as well as from non-glass materials (plastic, metal, ceramic, organic matter, etc.) is within the allowable limits. Otherwise, the recycling operation for glass, particularly in its broken form, may be too complex and costly [9]. This problem gave rise to recovery of glass for non-container uses (in secondary markets). The construction industry has made attempts to utilize waste glass in back-filling, roadway construction, pipe bedding, drainage applications, landfill gas venting layers and in many architectural and decorative applications such as glass tile, wall panels, etc. [9,10] In order to create another sustainable solution, extensive research has been conducted to understand the consequences of using waste glass as aggregate in concrete. These studies focused on determining the level of deleterious alkali–silica reaction (ASR) expansion arising from the reaction between cement alkalis and silica found in the amorphous structure of glass.

In the presence of glass aggregate, expansion characteristics will be influenced by particle size, chemical composition, thermal history of the glass, and the amount of glass in the mixture; however, their exact effects have not been well understood yet. Results of experiments by many authors are often in disagreement. Some researchers [11,12] reported that among the soda-lime glasses, green glass was less reactive due to a suppressing effect of the Cr_2O_3 found in its composition. On the contrary, according to Dhir et al. [13], green glass produced the largest quantity of expansion when compared to flint and amber glasses. Therefore, authors reported that rather than chemical composition of different colored glasses, the thermal history of glass during manufacturing process may be an important parameter since this factor plays a role in the levels of internal stress generated and the rate of leaching and dissolution of the glass. The particle size distribution of the glass is another feature that influences its alkali reactivity. Jin et al. [14] indicated that the size of clear soda-lime glass leading to the greatest amount of expansion (pessimum size) was 1.18 mm. However, during some other research studies, no pessimum size was observed and the coarser glass particles reacted to a greater extent [11,15,16].

2. Research significance

The method used to measure the reactivity of glass aggregate is of great importance. Although the accelerated mortar bar test is the most widely used method due to its being a rapid indicator, for compositions with glass aggregate, reliable test results may not be achieved [11,17]. The aim of this experimental study is to evaluate the influence of the particle size, chemical composition and amount of the soda-lime glasses on ASR expansion. For assessing ASR reactivity, three test methods (RILEM AAR-2, ASTM C1293 and the microbar test) whose details will be explained in this paper were followed.

3. Experimental details

3.1. Materials

Test specimens were manufactured using (1) CEM I 42.5 R type Portland cement (EN 197-1) with an alkali content of 1.03% in terms of equivalent Na_2O, (2) a non-reactive crushed limestone (CL), (3) flint glass aggregate (F) from post-consumer window glass, (4) green glass aggregate (G) from soda bottle waste, (5) amber glass aggregate (A) from beer bottle waste. The chemical compositions of the cement and aggregates are given in Table 1.

All aggregates were used up to 12.5 mm particle size. No chemical or mineral admixture was used in the study.

3.2. Applied procedures

There exist some studies in the literature dealing with the influence of various test methods on the degree of observed reactivity of different natural aggregate types [18,19]. By using aggregates with a wide variety of mineralogies and geographical origins, Ideker et al. [18] found that, while assessing the reactivity of fine aggregates, the results obtained by keeping the specimens at 38 or 80 °C correlated well with the results of outdoor exposure testing. In the current experimental study, three test methods (RILEM AAR-2, ASTM C1293 and the microbar test) were selected. Among these, AAR-2 [20] was proposed by RILEM TC 106-AAR (Alkali-Aggregate Reaction) and by raising the temperature to 80 °C, it enables a rapid assessment of potential reactivity of fine aggregate in question. Such accelerated tests are apparently fast ways of screening expansions; however, due to less severe test conditions and testing concrete rather than mortar, ASTM C1293-08b, "Standard Test Method for Determination of Length Change of Concrete Due to Alkali–Silica Reaction" [21] seems to have a higher reliability. Finally, a concrete microbar test that was proposed by Grattan-Bellew et al. [22] has the advantage of detecting the reactivity of coarse aggregates. This test applies the same storage conditions as in the AAR-2 test and it is expected that the results give further information about the particle size effect.

3.2.1. Concrete Prism Test (CPT)

As per ASTM C1293, a cement content of 420 kg/m^3 and a water/cement ratio of 0.42–0.45 by mass were used. This method requires the production of concrete prisms measuring 75 mm × 75 mm × 285 mm, while boosting the alkali content of the cement to 1.25% Na_2O equivalent by the addition of NaOH. After demolding at 1 d, initial length was measured and three prisms from each mixture were placed vertically over water at 38 °C in a sealed container. The length change was monitored over a period of 3 years.

Table 1
Chemical composition of cement and aggregates (% by mass).

	Cement	Limestone	Flint glass	Green glass	Amber glass
SiO_2	18.98	1.33	71.38	70.30	71.31
Al_2O_3	5.22	0.40	1.30	1.83	1.80
Fe_2O_3	2.39	0.33	0.107	0.311	0.97
CaO	63.90	53.88	8.28	10.07	9.15
MgO	1.01	0.53	4.27	3.00	2.16
SO_3	2.99	0.08	0.23	0.15	0.21
Na_2O	0.48	–	14.29	13.44	14.10
K_2O	0.84	0.18	0.07	0.59	0.21
TiO_2	–	–	0.076	0.059	0.080
Cr_2O_3	–	–	–	0.25	0.01
Cl^-	0.0007	–	–	–	–
LOI	3.73	41.20	–	–	–
Sum	99.54	97.93	100.00	100.00	100.00