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ALKALI AGGREGATE REACTIONS (AAR) IN CONCRETE

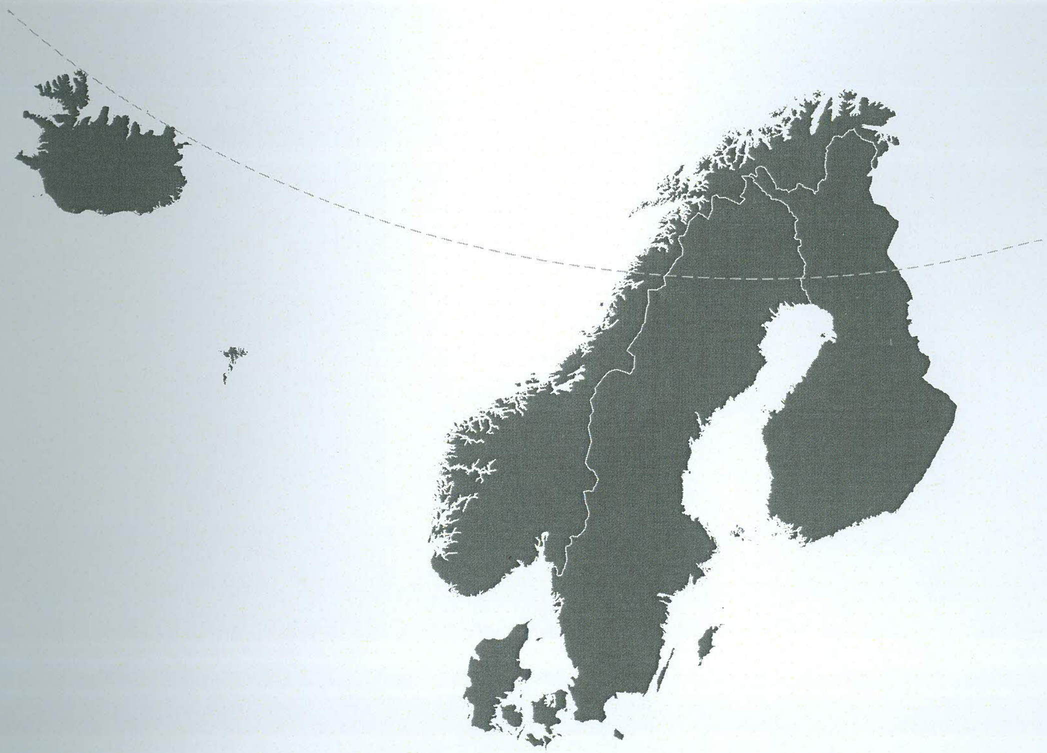
WORKSHOP PROCEEDING No. 11

THE NORDIC CONCRETE FEDERATION 2014

Workshop Proceeding No. 11

ALKALI AGGREGATE REACTIONS (AAR) IN CONCRETE

WORKSHOP PROCEEDING FROM A NORDIC - BALTIC MINISEMINAR
RIGA - LATVIA, 21. - 22. NOVEMBER 2013



Nordic
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PREFACE

This publication contains 8 papers presented at a Workshop (Nordic Mini Seminar) concerning Alkali Aggregate Reactions (AAR) in concrete.

The Nordic Concrete Federation aims to establish a closer connection with the Baltic countries. This workshop was therefore arranged in Riga in Latvia, with many participants from the three Baltic countries.

The workshop was organised by FARIN (Forum for AAR in Norway) and chaired by Børge Johannes Wigum from Mannvit/NorStone/NTNU. The Norwegian Public Roads Administration sponsored the event.

In order to stimulate discussions between the participants, the Workshop was arranged as a two-day residential course, November 21th – 22th 2013. Deleterious AAR in concrete structures are relatively recently revealed and documented in Finland and in the Baltic countries. However, in the rest of the Nordic countries, these reactions have been documented and studied for decades. Various contributions at the Workshop presented topics such as; Petrographic analyses of aggregate, Performance based testing of concrete, National- and international test methods and regulations, Diagnosis and appraisal in field structures and Structural consequences and rehabilitation.

35 researchers from Denmark, Finland, Iceland, Norway, Sweden, Latvia, Lithuania, Estonia and the Netherlands participated in the workshop.

The present publication is Number 11 in a special series of Workshop-Proceedings of the Nordic Concrete Research journal.

Nordic Concrete Research (NCR) is a bi-annual publication of The Nordic Concrete Federation, presenting research and practical experience in the field of concrete technology, both from structural and material perspective. Every third year one of the publications is devoted to abstracts from the Nordic Concrete Research Symposia. (Nordic Concrete Research – Research Projects 20XX). The next Concrete Research Symposium will be held in Reykjavik 13. to 15. of August 2014, and we look forward to meet you there.

Papers published in NCR are normally thoroughly reviewed by three reviewers. The papers in the present proceeding have however not been reviewed in this way. Instead the authors revised their papers after the workshop, based on comments and information obtained there.

Reykjavik, March 2014

Børge J. Wigum   Dirch H. Bager
Editor

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Challenge of ASR in the Use of Waste Glass Slurry

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ABSTRACT

Currently the majority of industrial companies in the world develop and implements clean production technologies where manufacturing wastes are recycled and are used for new building materials production. Due glass debris sorting and recycling are practiced at minimum level in Latvia, there should be found alternative ways how to reduce the accumulated glass wastes. The worldwide application of waste glass in concrete was quite limited due to alkali-silica reactivity (ASR) for almost forty years, but this supplementary cementitious material gained again interest in its alternative use in concrete industry in the last decade. It was found that the ground glass particles (<150 μm) initiate pozzolanic reactions without harmful expansion deformations. Size reduction of glass to enhance its chemical reactivity is the key enabling step for converting the landfill-bound waste glass into a valuable product capable of partially replacing cement in concrete. The coarse and fine aggregates can trigger ASR in concrete whereas glass powder can suppress the tendency to ASR and produce an effect similar to that of supplementary cementitious materials such as pozzolan. Waste glass is cementitious in nature when it is finely ground, and especially when it is ground in a wet environment. The obtained waste glass slurries with finest particle size up to 10 μm show pozzolanic characteristics. The ASR tests results indicate that the presence of finely ground waste glass in a wet environment has a relatively small influence on ASR expansion.

Key words: ASR, waste glass slurry.

1. INTRODUCTION

1.1 About glass

The term "glass," in a general sense, is applied to the hard, brittle, non-crystalline, transparent, opaque or translucent vitreous substance which results from fusing silica with active mineral solvents or fluxes, such as the alkalis, earthy bases, or metallic oxides. Silica exists in great abundance, in a free natural state, in the form of flints, quartz, and sand; and in the latter form it is now most generally used for glassmaking. When sand alkali and lead oxide are heated together to a high temperature, the sand is dissolved by the solvent action of the fused alkali and lead oxide until the whole becomes a molten mass of glass. The solvent action of the alkalis, soda potash or lead oxide, is very energetic whilst being heated, and the mass boils with evolution of gases until, at last, the solution, becoming complete, settles down to a clear quiescent molten liquid metal, which is quite soft and malleable, after the nature of treacle. In this condition it is ready for working. The time and temperature necessary for melting such mixtures vary according to the proportions and composition of the ingredients. Silica, combined with alumina and other oxides, is freely distributed in nature in the form of clays, granites, and feldspars, which are also available for use in glassmaking. Originally glass was made by using crushed and ground flint stones as the source for the silica: hence is derived the old name of "flint" glass; but now the large extensive deposits of white sand present a much more convenient and less expensive source, and sand has become universally used [1].

From the early days of the Ancient Egyptians the art of glassmaking was known, and it is now one of the most important industries, supplying as it does many articles for common domestic use and convenience. Nowadays, the large number of glass types can be classified in several ways, for example, by chemical composition use in the manufacture of glass products, or processing behaviour. The most widely used classification is by chemical composition which leads to three chief groups: soda-lime glass, lead glass and borosilicate glass. Glasses in these categories account for at least 95% of all glass types [2]. The remaining 5% are special glasses manufactured for the most part in very small quantities [3]. The European glass industry is very diverse and covers a variety of very different types of products and technologies, including bottles, jars, flat glass, continuous filament glass fibres (CFGF – not to be confused with insulation mineral wool), flaconnage, tableware, insulation mineral wool, optical fibres and special glass (cathode ray tubes, glass for televisions and monitors, lighting glass, optical glass, laboratory and technical glassware, borosilicate and glass ceramic cookware, etc) [2]. But at the same time due to progressive growth of urbanization increased glass production increases the rate of glass waste. Waste is a problem for the environment. But often, waste is also a resource which should be utilized in an environmentally efficient way [4]. Post-consumer waste glass can be recovered with the purpose of recycling in the glass manufacturing industry, to make products such as container glass, flat glass, etc. The process of recycling consists of a series of steps to condition the waste glass for further use. Typical steps are collection, crushing, sorting, contaminant removal, transport, and final use. Some of these steps can, if appropriate, be by-passed. When no use is found for glass, it is stored or disposed of. The most frequent disposal options are landfilling and incineration. Incineration implies that glass is mixed with other materials in slag, which then can be either used (e.g. in civil works) or landfilled. Disposal of glass waste is a complex problem for many countries in the world. Many governmental and nongovernmental organizations are dealing with this problem, but in spite of efforts, the recycling of glass in many countries is insufficient.

1.2 Glass waste recycling in Latvia

Approximately 50,000 tonnes of glass packaging waste is generated annually in Latvia (see Table 1). There are no recycling facilities for glass in Latvia [5], most of the glass waste is landfilled or exported by several companies dealing with preparation of glass for re-use to the neighbour countries. The opportunities for the recovery and recycling of different packaging waste vary between the countries. In Latvia, there is the only one lamp recycling centre in the Baltic States located in Liepaja, which in 2012 recycled 159 tonnes of lamp glass waste (see Figure 1). In Estonia, glass packaging factory exists (Jarvakandi klaas), but it requires a very good quality (the quality from the glass collected through the deposit system is good, but the quality from the glass collected through the containers is mostly not good enough (mixed glass)) and does not accept the green glass. Some of the glass is used to produce street pavements, stones etc, the rest is still exported. Several other recycling projects are in a certain stage, getting 50 % support from the EU Cohesion program. But they are still unable to proceed, as there is no clarity around the waste sector is still too big for the financial institutions to provide rest of the financing [6]. There are four glass recycling companies in Lithuania (CJSC "Kauno stiklas", JSC "Warta Glass Panevėžys", CJSC "Alytaus keramika", CJSC "Stikloporas") which have quite a high glass recycling capacity (54.7 kt/a) [7], thus, this waste is even imported.

Table 1 – Packaging waste recycling statistics in Latvia within 2003- 2011 years [8-16]

Year	Latvian purchased glass packaging waste (t)	The imported glass packaging waste (t)	Exported glass packaging with goods (t)	Generated glass packaging waste (t)	Reused glass packaging waste (t)	The collected glass packaging waste (t)	Glass packaging waste exported for recycling (t)	Glass packaging waste recycled in Latvia (t)	The total volume of recycled glass packaging (%)	Reclaimed glass packaging waste (t)	Reclaimed glass packaging volume (%)
2003	32585	45034	15826	62193	29010	15829	3333	12523	26	15856	26
2004	44416	55817	18307	73771	27201	24014	7474	14503	30	11851	16
2005	260	4	110	58565	----	----	5786	21558	47	----	----
2006	9682	19445	16609	63639	5173	----	10970	23998	55	----	----
2007	9202	30592	4555	78973	87	----	13122	22917	46	10	----
2008	----*	----	----	66788	----	----	15324	35424	----	----	----
2009	----	----	----	44323	----	----	6692	19690	----	----	----
2010	----	----	----	51896	----	----	7648	24704	----	----	----
2011	----	----	----	51967	----	----	7731	26814	----	----	----

* ---- data is not reflected in the reports

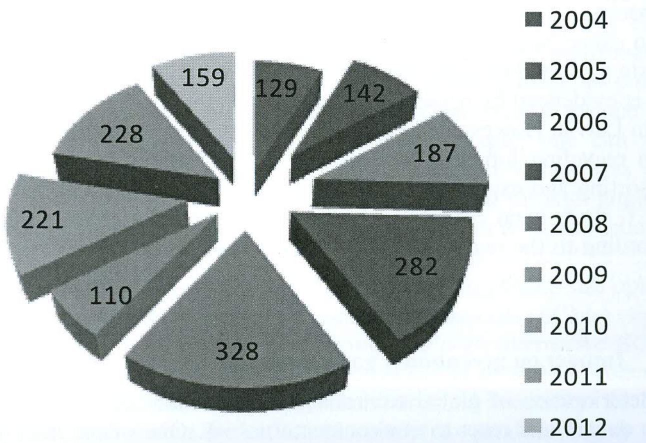

Figure 1 – Incandense lamp and fluorescent tubes recycling statistics [17]

In the middle of the 1990's the Baltic States developed and adopted National Environmental Strategies/Plans in which improvement of the waste management system was defined as one of the main priorities of the national environmental policy. Recognising waste management as a priority for environmental policy, various strategies and plans have been elaborated with the aim of developing an efficient waste management system complying with the European Community's and other relevant international waste management policy principles and requirements. Considering the economic value of the secondary raw material, recovery and recycling schemes for packaging waste were established in many countries even before comprehensive EC legislation was adopted. With the Directive 94/62/EC on Packaging and Packaging Waste, the European Community, as a first priority, aimed to prevent the production of packaging waste and, secondly, to encourage the reuse, recycling and other forms of recovery of packaging waste, to reduce the amount that is disposed of in landfills. Based on the actual amount of packaging waste generated and the availability of recovery and recycling facilities, Latvia has developed directive specific implementation plans for achieving the targets laid down in Directive 94/62/EC [18]. In conjunction with economic growth and increased consumption, packaging amounts (defined as all products made of any materials of any nature to be used for the containment, protection, handling, delivery and presentation of goods that, when discarded) ending up in waste streams during all this time were increasing. Packaging waste was generated along with municipal waste (household and commercial waste). Due to a lack of a separate collection system, packaging waste has mainly been disposed of at landfills. Although certain steps to promote recovery and recycling have been taken, comprehensive reporting on the whole packaging waste management chain has not been performed. The total amount of separately collected packaging waste was less than 5% of the total municipal waste stream in 2002. And that indicated a weakness in the existing reporting/collection system. When, for example, Estonia introduced an excise tax on beverage packaging in 1997, with the goal of increasing recovery and recycling, due to high tax rate, almost all of the companies fulfilled packaging waste recovery targets. In 2003 a new instrument – a deposit system for glass bottles - to increase reuse of refillable glass packaging was introduced in Latvia. The packaging waste management system in Latvia became based on the "producer responsibility" principle - producers and importers are required to organise the packaging waste management system. There were recently founded packaging management organisations whose aim is to improve the situation by establishing separate collection systems also promoting the collection and primary sorting of packaging waste due to that mostly depends on the goodwill and awareness of the public, as so called habit of each citizen to sort wastes at the first place. In 2013 waste sorting (mainly waste glass and plastics) has become more popular in Latvia than it was in the previous years. This is evidenced by presence of special waste separation containers and drop-off points for wastes in Latvia. However, there is still absence of factories that could recycle glass wastes and Latvian recycling infrastructure is based mostly on limited operations like: waste glass collection, sorting and export to EU. As there is absence of data in statistics, as it can be seen from Table 1, there is no complete statistics on waste glass collected and recycled amount in Latvia, according to the regulations the total amount which should be recycled yearly is 50%, and that is shown but other items are not reflected in the last year reports.

1.3 Impact on greenhouse gas emissions

The rapid deterioration of global environmental conditions indicated to society the increasing necessity to debate and react to environmental issues. One of the most important and debated issues is the enhanced greenhouse effect. The Intergovernmental Panel on Climate Change (IPCC) has predicted global rise in temperature and carbon dioxide is a major greenhouse gas responsible for global warming. The Kyoto Protocol was opened for international support on December 11, 1997 at Kyoto, Japan. The main objective of the Kyoto Protocol is to stabilize the greenhouse gas concentrations in the atmosphere, by bringing them to a level that will not interfere with the climate system. Under Kyoto protocol some countries committed to reduce their Greenhouse Gas (GHG) emissions 5.2 % compared to 1990.

According to the International Energy Authority World Energy Outlook 1995, worldwide cement production was responsible for 7% of the total CO_2 emitted around the world [19]. Approximately, half of the CO_2 emitted by the cement industry originates from the fuel and half from the calcinations (chemical reaction) that will convert raw materials into clinker. To produce one tonne of Portland cement clinker in a rotary kiln, some 100 kg of fuel oil is used for the electric energy generation. To make Portland cement, clinker has to be ground to fineness in excess of 300 m^2/ kg. Grinding requires between 35 and 40 kilowatt hours (i.e. 126 - 144 MJ) of electric energy per tonne of clinker, or about 10 kg of fuel oil. Apart from oil, pulverised coal and natural gas, or dual fuels, such as oil-coal, oil-natural gas, and coal-gas are commonly used for clinker making. An average CO_2 emission factor in the fossil fuel combustion process is of the order of 0.22 kg of carbon dioxide for every kilogram of fuel. The electrical energy requirement to produce one tonne of cement is of the order of 440 kWh or approximately 1.580 MJ [20]. Calcination of one tonne of $CaCO_3$ generates 440 kilograms of CO_2, according to the stoichiometry of this chemical reaction. Energy demand for the calcination of one tonne of clinker is about 490 kWh, or approximately 1.750 MJ. Consequently, for every tonne of Portland cement produced, cement plants generate approximately one tonne of carbon dioxide - one of the main greenhouse gases [21]. This figure varies, depending on the type of kiln and the fuel used. For a wet process, common in the developing countries, it is near 1.1 tonnes of CO_2 per tonne of cement; for a more energy efficient dry process it is of the order of 0.9 tonnes of carbon dioxide per tonne of cement, but a tonne per tonne is a good average.

1.4 Waste glass in concrete

Rapid depletion of resources and concerns over degradation of the environment has led to a growing emphasis on sustainable development [22]. As a result, the construction industry is required to adopt environmentally friendly practices and make judicious use of natural resources. The concrete industry can address growing environmental and energy concerns by minimizing the cement content in concrete required to meet the required performance levels; this goal can be accomplished by replacing as much of Portland cement as possible with pozzolanic supplementary cementitious materials (SCMs) [23]. In order to reduce the carbon footprint and the consumption of energy in production of concrete, one can reduce the consumption of concrete, reduce the cement content of concrete, or reduce less clinker for cement production [24]. The consumption of concrete can be reduced through implementation of innovative architectural concepts and structural designs for new construction and for rehabilitations of old structures. The cement content in concrete can be reduced through changes in concrete mix designs (e.g., use of high-range water reducers and aggregate size optimization), partial replacement of cement with supplementary cementitious materials (SCMs) (fly ash, blast furnace slag, natural pozzolans, waste glass). When compared with alternative SCMs, waste glass actually offers a more favourable chemistry for effective use as an SCM in concrete. Glass, which is rich in amorphous silica, has the proper chemistry and reactivity for pozzolanic reactions with the lime released during hydration of cement to produce highly stable end products with desired binding qualities. The recycling of glass in concrete as partial replacement of cement offers three major benefits. First, waste glass has negative value when disposed of in landfills, requiring tipping fees; it assumes a considerable positive value as partial replacement for cement in concrete. Second, as partial replacement of cement, waste glass reduces the significant polluting effects, energy consumption and cost of producing Portland cement. Third, the use of waste glass in concrete as partial replacement of cement yields enhanced physical, mechanical and durability characteristics through pozzolanic reactions with cement hydrates.

Recycling of post-consumer glass for use as raw material in production of new glass is very limited by difficulties related to the classifying operations of the mixed waste glasses. Landfilling of waste glass is not only an expensive way of disposal with a tipping fee of $65 per ton (2001 data), it also occupies increasingly scarce landfill space available in urban areas [25]. Since glass is not biodegradable, its disposal in landfills is not an environmentally friendly solution. There is a strong need to utilize the waste glass in an environmentally friendly way. One option is to recycle waste glass in construction materials, including concrete, where the chemistry of glass can make contributions towards the end product quality [26-31]. So far, the construction industry has made low-value use of waste glass (cullet) as replacement for aggregate.

In the sixties, many studies have been devoted to use crushed glass waste as an aggregate for concrete production [32-34]. This aggregate was also applied in road construction. The glass waste was also used for production of glass tiles and bricks, wall panels, glass fibre, agriculture fertiliser, landscaping reflective beads and tableware [35]. Many other alternatives have been proposed to use waste glass as glasphalt, abrasives, filtration media, binders in ceramics and bricks, additives and fluxes in metal foundry work and as additive for cements [25, 27]. The properties of glass seemed comparable to those of large aggregate in terms of constitution, strength and durability, and the larger size of the glass meant lower processing costs. These early attempts however, were unsuccessful due to the alkali–silica reaction (ASR) which takes place in the presence of the amorphous waste glass and concrete pore solution with marked strength reduction and simultaneous excessive expansion [36]. A pozzolanic material is a siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide to form compounds possessing cementitious properties. It has been demonstrated that such materials require high silica content, an amorphous state and a large surface area [36]. Many industrial wastes or by-product powders, which possess pozzolanic properties, have already been successfully used in concrete mixtures such as fly ashes, granulated blast furnace slags, steel slags [37] and silica fume [38]. Due to high disposal costs of glass wastes, the use of glass as concrete aggregate again attracted the attention of researchers [26, 39-41]. Waste glass offers a highly desirable chemistry for use as a SCM. Size reduction of glass to enhance its chemical reactivity is the key enabling stop for converting the landfill-bound mixed-colour waste glass into a valuable produce capable of partially replacing cement in concrete. This highly promising concept has not, however, been picked up by the cement and concrete industry.

1.5 ASR

Alkali-silica reaction (ASR) is the reaction that occurs between hydroxyl ions in concrete pore water and certain forms of silica which may be present in some aggregates. The product of this reaction is a gel which imbibes water and swells. If sufficient reaction and swelling takes place, the pressures induced cause micro-cracking, expansion and ultimately deterioration of the surrounding concrete.

Recent publications, whilst not specifically supporting the use of glass in concrete, have led to a great understanding of ASR parameters and methods by which it can be suppressed and major recent research in the USA and UK [42; 43] has made it possible for recycled glass to be viewed as a potentially “fit-for-purpose” concrete construction material.

Experimental results have demonstrated that both particle size and chemical composition have an influence on the expansion during alkali-silica reaction [42, 44]. Generally, the finer glass particles exhibit considerably lower expansion; pozzolanic activity increases as fineness increases. Fine particles of waste glass powder also tend to perform a relatively rapid pozzolanic reaction with Portland cement on the contrary to the much slower alkali-silica reaction.

The particle size of glass aggregate was found to have a major influence on ASR expansion. Since the ASR reaction is clearly a surface-area dependant phenomenon, one would expect the ASR associated expansion to increase monotonically with aggregate fineness [42]. However, there exists a size of the aggregate at which the maximum expansion occurs. This is called “pessimum” size, which for regular finer than the pessimum size, processes other than the surface-area dependant become predominant and the expansion decreases with further fineness. In fact, when waste glass was ground to mesh size #50 (300 µm) or finer, no expansion of glascrete mortar bars was observed. This means that the ASR expansion increases with increasing fineness of glass particles up to certain point, and then decreases afterwards [42]. The practical implication of this finding is that waste glass, ground to at least mesh size #100 (150 µm), is not likely to cause unacceptable expansion due to ASR.

It was found that if glass was ground to a particle size of 300µm or smaller, the ASR induced expansion could be reduced and in fact, data reported in the literature that if waste glass finely ground under 75µm, this effect does not occur and mortar durability is guaranteed [36]. Despite the high alkali content of glass, which may represent a typical concern for its use in concrete, studies [44, 30] have shown that finely ground glass does not contribute to alkali-silica reactions. When glass ground to about the same fineness as Portland cement or even finer, below 100 µm, for example in a wet environment [45], waste glass powder has advantageous pozzolanic behaviour: the amorphous silica (SiO_2) reacts with portlandite ($Ca(OH)_2$) generated during cement hydration to form gel of calcium silicate hydrate (CSH).

2. MATERIALS AND METHODS

2.1 Supplementary cementititous material (SCM) – Waste Glass Slurry

Since the chemistry of different types of glass is different, one would expect different ASR expansions. Various types of glass waste cullet were tested, including: soda-alkaline earth-silicate glass (LB) coming from low pressure mercury-discharge lamp waste chips and borosilicate glass (DRL) coming from incandescent light bulb and low pressure sodium lamp waste chips were received from a local lamp recycling centre located (kindly supplied by Agris Magone, Liepaja, Latvia); soda-lime glass cullet was obtained from beverage containers ((F) flint colour) which was collected from a local glass bottle return point and manually by hand crushed into chips under laboratory conditions.

In order to obtain waste glass slurries, washed and dried waste glass chips with total volume of material of 500 grams in each of four containers of laboratory planetary ball mill Retsch PM400 were ground with rotation speed 300 min^{-1} for 120 minutes in a wet environment with water to glass proportion 1:1 by weight (see Figure 2). In total were prepared four kinds of slurries: DRL, LB and F.

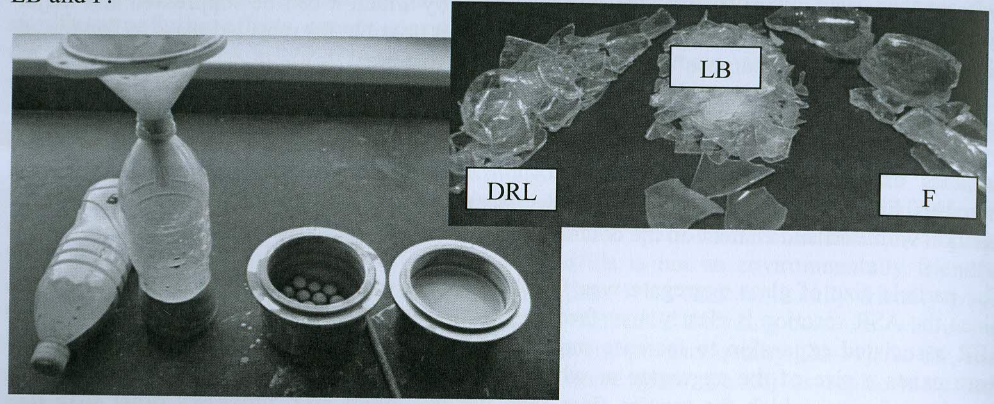

Figure 2 – Waste glass cullet and slurry

Borosilicate glasses

Silicate glasses containing boric oxide have a higher percentage of SiO_2 (70-80%) than soda-lime and lead glasses. Characteristic of this type is the presence of substantial amounts of silica (SiO_2) and boric oxide (B_2O_3> 8%) as glass network formers. The amount of boric oxide affects the glass properties in a particular way. Apart from the highly resistant varieties (B_2O_3 up to a maximum of 13%) there are others that – due to the different way in which the boric oxide is incorporated into the structural network – have only low chemical resistance (B_2O_3 content over 15%) [46]. Glasses having such a composition show a high resistance to chemical corrosion and temperature change. For this reason, they are used in process plants in the chemical industry, in laboratories, as ampoules and vials in the pharmaceutical industry, as bulbs for high-power lamps and low pressure sodium lamps. But borosilicate glasses are also used in the home; backing and casserole dishes and other heat-resistant items can be made from it. The family of borosilicate is extremely broad, depending on how the boron compounds within the glass melt interact with other metallic constituents.

Alkali-lead silicate glasses

Such glasses typically contain over 10% lead oxide (PbO). Lead glasses containing 20–30% PbO, 54–58% SiO_2 and about 14% alkalis are highly insulating and therefore of great importance in electrical engineering. They are used in lamp stems. Lead oxide is also of great importance as an X-ray protective component (radiation shielding glass and cathode ray tube components). In the beginning of 19th century lead silicate was composed of 100 parts sand and 66 parts of red lead fused together. This silicate was mostly used in the manufacture of soft enamels and artificial gems, and went under the names of “Rocaili flux”, “strass metal” and “diamond paste” [1].

Fluorescent lamps are low pressure mercury-discharge lamps which have a fluorescent substance coating the inside of the tube using only 20 to 25% of the energy required for incandescent and other lighting technologies. Installation of high-efficiency lamps reduces the demand for electricity, which in turn reduces the amount of mercury and green house gas (GHG) emissions from utility boilers, particularly coal-fired boilers. In the tube, made of soda-alkaline earth-silicate glass, mercury vapour is excited to produce ultraviolet radiation, which is transformed into visible light when it strikes the fluorescent material coated on the inside of the glass tube. Due to the high ultraviolet absorption of the fluorescent material as well as the glass, no ultraviolet light is emitted from the tube. Here again, lead glass is used to seal the electric leads into the sockets of the tube.

Alkali alkaline-earth silicate glasses (soda-lime glasses)

By far the greatest number of industrially produced glasses belongs to a group of glass types with very similar composition, collectively called the soda-lime glasses. As the name indicates, soda and lime play a major role along with the main component, sand. This is the oldest glass type. A typical soda-lime glass is composed of 71-75% by weight sand (SiO_2), 12-16% soda (sodium oxide from the raw material soda ash or sodium carbonate), 10-15% lime (calcium oxide from the raw material limestone or calcium carbonate), and a low percentage of other materials for specific properties such as colouring. Sometimes magnesium replaces a portion of the calcium contained in the limestone, or potassium replaces the sodium in the soda. Even so, these glasses are similar to and may be classified as soda-lime glasses. Soda-lime glass is primary used for bottles, jars, everyday drinking glasses and window glass.

2.2 Supplementary cementititous materials (SCMs) – Fly ash, wood ash and metakaolin

Fly ash Cemex 450-1 S (FA) was obtained in UK. Wood ash (WA) was obtained in Latvia. Metakaolin (MK) was obtained by heating kaolin at temperature of 800°C for 3 hours in the high temperature universal precise laboratory electric furnace (SNOL 8/1600L). The chemical composition and particle size distribution of SCMs are given in the Tables 2 and 3.

2.3 Cement

Two different cements were used to determine potential deleterious reactions between waste glass slurry and cement matrix. The chosen cements are locally available in Latvia: Kunda-Heidelberg CEM I 42.5N (Estonia) and Aalborg CEM I 52.5R (Denmark).

Table 2 – Chemical composition and Na_2O equivalents of cements and SCMs

Cement & SCMs	Bulk oxide, mass (%)											Na_2Oeq (%)	K*
	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MnO	MgO	TiO_2	SO_3	P_2O_5		
Kunda	17.93	5.22	2.97	62.03	0.20	1.76	0.14	4.06	0.36	3.76	0.44	1.36	3.71
Aalborg	23.16	2.40	0.30	68.87	0.25	0.06	0.02	0.81	0.07	2.23	0.33	0.29	3.04
DRL	71.14	2.60	0.17	1.320	3.30	1.70	0.006	0.62	0.006	0	0.023	4.42	0.05
LB	65.52	1.22	0.11	5.11	12.35	1.88	0.01	2.95	0.027	0.14	0.038	13.59	0.08
F	69.61	1.34	0.08	11.30	11.21	0.56	0.008	0.46	0.028	0.13	0.021	11.58	0.16
FA	42.1	19.6	10.3	3.3	1.7	2.7	0.1	1.3	1.0	1.8	0.4	3.47	0.52
WA	40.69	14.1	8.29	13.5	0.43	1.34	0.178	3.49	0.631	0.55	0.745	1.29	0.67
MK	46.0	38.0	1.10	0.10	0.20	1.0	-	0.18	0.58	-	-	0.858	0.825

*K – the reactivity index defined as $K=(CaO+Al_2O_3)/(SiO_2+Na_2O)$ [47]

The fineness of cements and SCMs was obtained by automatic Blaine apparatus Zwick/Roell ToniPERM using the rapid method without the need to measure density of the powder beforehand with a pyknometer in accordance with BS EN 196-6 [48] and ASTM C204 [49]. The chemical analysis of the investigated materials was performed in conformity with BS EN 196-2 [50] and Na_2O equivalent as the most significant contributors to ASR expansion was defined (see Table 3).

Table 4 – Particle size distributions and Blaine fineness of cements and SCMs

Cements & SCMs \ Volume mean diameter,µm	d(0.1)	d(0.5)	d(0.9)	Blaine fineness (cm^2/g)
Kunda CEM I 42.5 N	3.536	21.213	62.051	3888
Aalborg CEM I 52.5R	3.078	14.045	45.330	3580
DRL 1/1/120	0.713	2.835	8.088	-
LB 1/1/120	2.473	8.970	20.088	-
F 1/1/120	1.151	3.306	8.932	-
FA	2.025	13.994	56.281	4360
WA	3.592	21.630	76.254	6600
MK	3.696	11.904	33.096	-

2.4. Preparation and curing of the mortar bar specimens

Mortar bar specimens were prepared following the procedure described in RILEM TC 106 AAR-2 "Detection of potential alkali-reactivity of aggregates – the ultra-accelerated mortar - bar test"[51]. In order to cast mortar bar specimens with dimensions 25x25x285mm, prismatic ply wood moulds were designed. Stainless steel pins of 6 mm diameter and 20 mm length used for length measurements were fixed in the centres of the end plates of the moulds before the casting procedure (see Figure 3).

There were prepared 39 mortar bar specimens for each cement type and three types of waste glass slurries: 3 reference mortar bar specimens, 9 mortar bar specimens with cement substitution with waste glass slurries at 20 wt. %, 27 mortar bar specimens with cement substitution with waste glass slurries at 20 wt. % and fly ash (FA) at 10 wt. % or wood ash (WA) at 10 wt. % or metakaolin (MK) at 10 wt. %. The mortars were mixed in accordance with the procedure for testing the strength of cement with plastic mortar according to LVS EN 196-1 [52]. Three specimens per each batch were made. The mortar workability was measured by flow table test according to LVS EN 1015-3 [53] and was in range of 210-220mm, a superplasticizing agent Sika Visco Crete D 132-2 was added to the mortar mixtures in order to achieve the required flow.

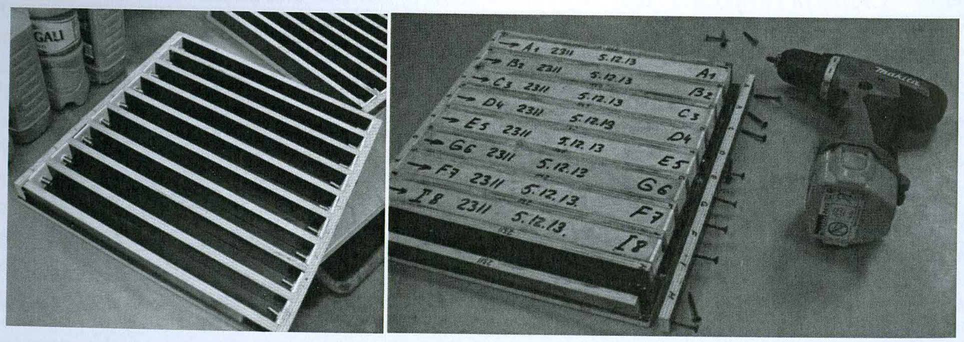

Figure 3 – Preparation of the mortar bar specimens for ASR test with dimensions 25x25x285mm

The mortar bar specimens were cured for 1 day at 20±2°C and 95% relative humidity in the moulds, after 24 ± 2 h they were demoulded and their initial length was measured. The specimens after were placed in water, transferred to an oven at temperature 80±2°C for 24 h, removed from the waster and the length measured immediately before the temperature has dropped substantially. After the specimens were placed in 1 M NaOH solution already at a temperature of 80±2°C, the containers were sealed and placed in an oven at 80±2°C (subsequently 14 days). Length measurements were taken only on 7th and 14th days by means of an electronic comparator (±0.001 mm accuracy).

3. RESULTS AND DISCUSSION

3.1 Expansion tests

The linear expansion of each specimen was obtained by calculating the difference between the length of the specimen at each period of measurement (L_n) and the zero measurement (L_o), to the nearest 0.001% of the effective length, as follows:

$$Expansion,\% = 100 \cdot (L_n - L_0) / \text{Gauge length} \tag{1}$$

where L_n - reading taken at each period of storage in sodium hydroxide solution, L_o - measurement of specimen before subjection to sodium hydroxide solution, *Gauge length* - distance between inner ends of the metal pins, measures to the nearest 1mm.

According to AAR-2, the aggregates are classified:

- innocuous, if expansions are smaller than 0.10% at 16 days;
- potentially reactive, if expansions are between 0.10% and 0.20% at 16 days;
- reactive, if expansions are greater than 0.20% at 16 days.

The main obstacle to the study of ASR, specifically, the potential reactivity of certain aggregates, is the long-term nature of ASR. The resulting damage can take many years to manifest itself, therefore, accelerated test methods are needed that either compress the material's service life into a reasonable time frame or exaggerate certain reactions in such a way as to enable efficient comparative studies [44]. Nowadays the AAR-2 is considered as not as reliable as it should be due to the test is severe (due to the harsh test conditions which are not representative of the service life encountered by actual concrete structures) and many aggregates that have good behaviour in the field were classified as reactive, and some others that passed the test were found to induce cracking due to the alkali-aggregate reaction (AAR) in concrete [54]. However, it is the most effective of the RILEM methods across the whole range of European aggregates investigated, including the identification of "slowly" reactive aggregate combinations [55]. And it is still the only way to check reactivity of aggregates in a very short time period and several countries have proposed different limits and ways of performing the test.

Figures 6-9 show the expansion of 26 mortars at 16 days. According to the obtained results, it can be seen that only 6 mortars pass the test and are innocuous.

Borosilicate glass lamp waste (DRL) slurry performs the lowest expansions. When is used Kunda cement (with higher alkali level in comparison to Aalborg cement and also high expansions for the reference mortars in range of 0.14-0.15%), DRL performs lower expansions in the combination with metakaolin (0.039% for Kunda) and fly ash (0.06% for Kunda). When is used low alkali cement (Aalborg) the expansion is 0.05%, the expansion of the reference mortar is 0.06%.

Kunda cement has low Na_2O_{eq} (see Table 3) therefore the expansion results for DRL slurries are lower (see Figure 6) and the application of fly ash and metakaolin in the mortars shows the best performance for the experimental programme in the present study.

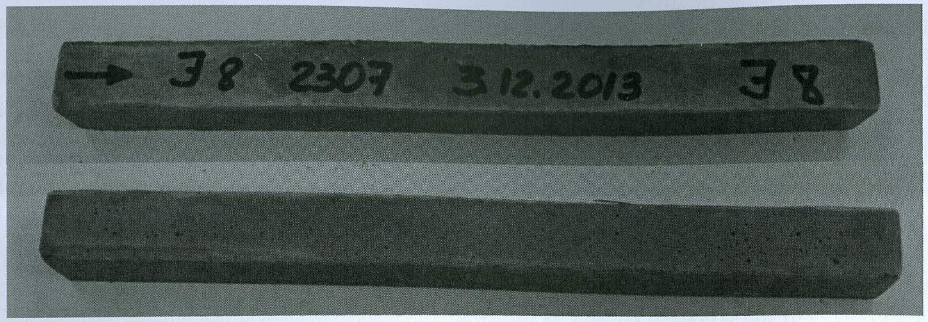

Figure 4 – The mortar bar specimens (Kunda+DRL slurry+MK) before ASR test

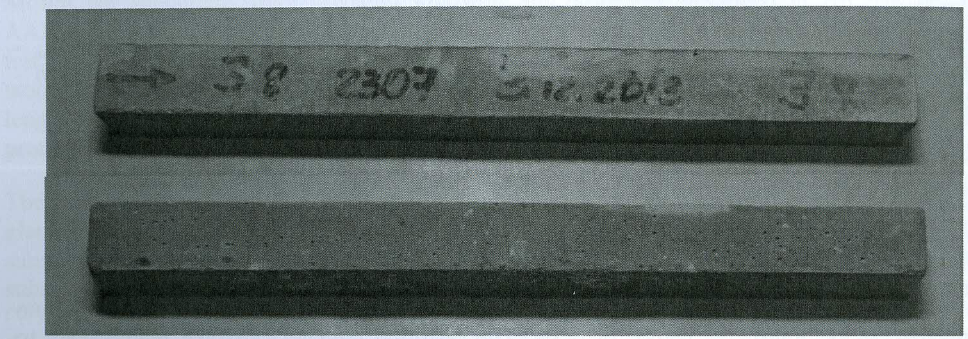

Figure 5 – The mortar bar specimens (Kunda+DRL slurry+MK) after ASR test

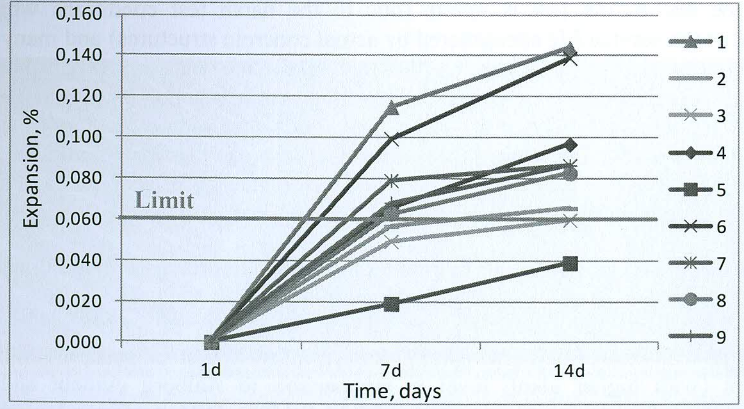

Figure 6 – ASR test results for the mortar bar specimens with Kunda Portland cement: 1) reference specimen, 2) DRL slurry, 3) DRL slurry +FA, 4) DRL slurry +WA, 5) DRL slurry+MK, 6) LB slurry, 7) LB slurry + FA, 8) LB slurry + WA, 9) LB slurry +MK

F slurry in combination with Kunda cement is potentially reactive, the application of WA and MK raise the expansion value over 0.08% (see Figure 7).

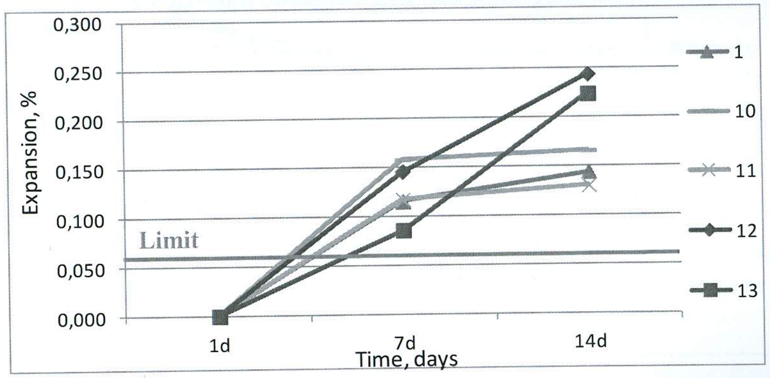

Figure 7 – ASR test results for the mortar bar specimens with Kunda Portland cement: 1) reference specimen, 10) F slurry, 11) F slurry + FA, 12) F slurry + WA, 13) F slurry +MK

Soda-alkaline earth-silicate glass (LB) slurry performs the lowest expansions with Aalborg cement (0.06%).

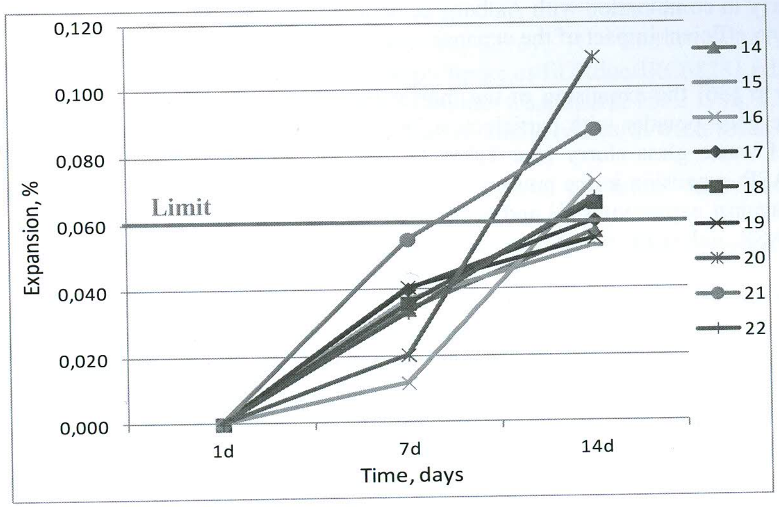

Figure 8 – ASR test results for the mortar bar specimens with Aalborg Portland cement: 14) reference specimen, 15) DRL slurry, 16) DRL slurry +FA, 17) DRL slurry +WA, 18) DRL slurry+MK, 19) LB slurry, 20) LB slurry + FA, 21) LB slurry + WA, 22) LB slurry +MK

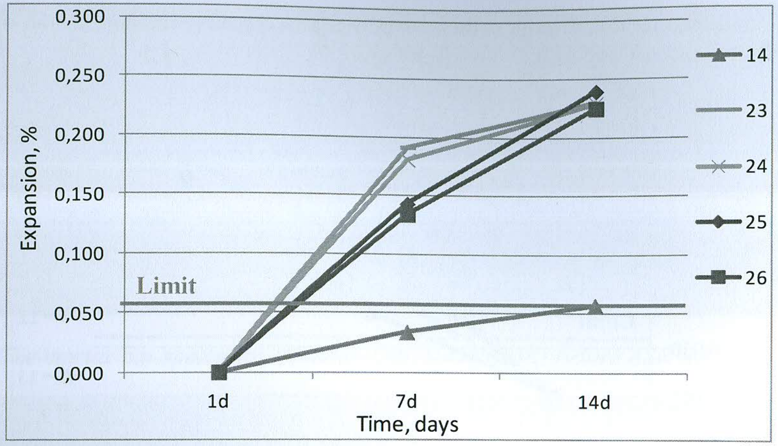

Figure 9 – ASR test results for the mortar bar specimens with Aalborg Portland cement: 14) reference specimen, 23) F slurry, 24) F slurry + FA, 25) F slurry + WA, 26) F slurry +MK

DRL and LB slurries in combination with Aalborg cement are innocuous. The application of fly ash and metakaolin to DRL and LB mortars with Aalborg cement raise the expansions, therefore its application is not reasonable (see Figure 8), however only DRL slurry can be applicable with WA. F slurry in combination with Aalborg cement are reactive, the application of FA, WA and MK gives no efficient impact of the expansion reduction (see Figure 9).

According to [36] the expansion of the mortar bar with 30% cement replaced by fluorescent lamp waste glass powder with particle size 38 µm was reduced to half of that in control. The particles of waste glass slurry (see Table 3) are finer and are below 38 µm and there was observed ASR expansion in the present investigation. However, fineness of aggregate size is no guarantee against expansion [56] and even highly pozzolanic materials cannot be guaranteed to be free of ASR, unless the particles are fine enough [44].

The pessimum size depends strongly on the reactivity of the aggregate, as the aggregate becomes more reactive, the pessimum (particle size that causes maximum expansion) shifts towards smaller particle size [44]. In the present investigation, it is evident that for example DRL has the finest particles therefore it should be the most reactive aggregate, but it is not, the expansion is less than to the reference mortar and LB, F mortars. The expansion of mortar bars is directly proportional to the glass content, higher substitute level – higher expansion, therefore for the present investigation was chosen optimum substitution at level of 20%.

4. CONCLUSIONS

The locally available Portland cement Kunda is potentially reactive; its Na_2O_{eq} doesn't correspond to the requirements according to LVS EN 197-1 [57]. The application of soda-lime glass cullet in concrete with Portland cement Kunda can cause negative effect on durability; however the application of low pressure mercury-discharge lamp, incandescent light bulb and low pressure sodium lamp waste cullet can significantly reduce the expansion making mortars with Kunda innocuous.

The combined use of other supplementary cementitious materials such as fly ash, wood ash and metakaolin not always has positive effect on mitigation of the expansion; as it was observed in the present investigation, it depends on cement type and waste glass used.

The colour of the container glass is normally obtained by adding certain oxides to the glass melt, therefore these oxides of waste glass slurry have significant effect on the ASR results. However, it cannot be postulated that the expansions of mortar bars are strongly dependent on the colour of the glass due to transparent glass (flint colour) can belong to soda-alkaline earth-silicate glass or to borosilicate glass or to soda-lime glass. Therefore, the expansions of mortar bars are strongly dependent on chemical composition of the glass and its fineness.

Substitution of cement with waste glass slurry can offer a slight economic advantage, however environmentally friendly materials, which are produced to save natural resources by using recycled materials, are gaining in popularity worldwide.

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