Performance of waste glass powder (WGP) supplementary cementitious material (SCM) – Drying shrinkage and early age shrinkage cracking

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Abstract

EU laws have been the most effective driving force of Latvian and Hungarian environmental legislation in order to improve recycling of packaging waste. In Latvia and Hungary the waste diversion strategies have focused on establishing treatment capacity and setting up schemes for separate collection, which largely cover packaging waste. Despite all improvements done in this area, still large amount of glass wastes is dumped into landfills and alternative solution for this waste glass utilization could be the application in concrete as a supplementary cementitious material (SCM). Laboratory tests were carried out on cement paste specimens, in which waste glass powder (WGP) addition was used as a SCM. Cement was substituted with WPG at levels of 20% or 30% per mass. It was demonstrated that the WGP addition is applicable in view of drying shrinkage with total deformation up to 2.5 ‰ in the period of 592 days. The WGP addition contributes to a slowdown in the rate of hydration of the cement paste, so the early age shrinkage cracking tendency becomes more favourable, which can be seen in the longer cracking time result during the ring tests.

Keywords: recycling, waste glass, supplementary cementitious material, drying shrinkage, early age shrinkage cracking

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1. Introduction

Both industrial and municipal wastes are key environmental, social and economic issues and a growing problem, since the amount of waste generated in European continues is rising each year. Waste management has become increasingly sophisticated, since separate collection and recycling facilities have become commonplace and landfill and incineration standards have become more rigorous. However, rising global consumption patterns put increasing pressure on ecosystems and waste infrastructure [1]. Greenhouse gas emission is also becoming more and more relevant in waste management planning. In countries that have very low landfill rates, waste recycling and energy recovery can help avoiding greenhouse gas emissions from the production of material or energy [2]. As an example, the use of 1 ton of cullet (crushed recycled glass), in comparison with 1 ton of natural raw material (sand), releases 500 kg less of carbon dioxide (quarrying, transport and fusion included).

Since Hungary and Latvia have joined the European Union (EU) in 2004, EU laws have been the most effective driving force of Hungarian and Latvian environmental legislation in order to improve recycling of packaging waste. In Hungary and Latvia the waste diversion strategies have focused on establishing treatment capacity and setting up schemes for separate collection, which largely cover packaging waste.

Hungarian performance in terms of municipal waste management recycling has been improving considerably over the last decade from close-to-zero (2 % in 2001) to 21 % in 2010, while at the same time municipal waste management generation has decreased by 13 % and decoupled from economic growth over 2001-2010. If the increase rate for recycling of the last 5 years can be maintained, then the recycling rate would reach 47% in 2020 which is slightly under the 50 % target set in the EU legislation for 2020 [3]. It is estimated that the municipal waste management contained around 5.9 % glass in Hungary in 2012 [4]. 20 000 tons are recycled annually by Maltha Ltd. and the rest of glass waste is exported mostly to the Czech Republic.

Approximately 50,000 tons of glass packaging waste is generated annually in Latvia. 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 the presence of special waste separation containers and drop-off points for wastes in Latvia. However, there is still absence of factories [5] which could recycle glass wastes and Latvian recycling infrastructure is based mostly on limited operations like: waste glass collection, sorting and export to EU by several companies dealing with preparation of glass for re-use to the neighbour countries.

2. Durability aspects of the application of waste glass as supplementary cementitious material

Millions of tons of glass cullet are landfilled throughout the planet every year. Over the last two decades, several studies have been carried out by researchers to solve the disposal problem of glass cullet [6]. The concrete industry is one of the potential users of reusing millions of tons of glass cullet per year either as aggregate or supplementary cementitious material (SCM). However, durability concerns over alkali-silica reaction (ASR) have limited the use of glass as a fine aggregate replacement in concrete [7]. Several studies have shown that glass behaves pozzolanically if ground finely enough, with a specific surface area of more than 300 m^2/kg [8-13]. Towards sustainable development only a few studies were published on the investigation of drying shrinkage and early age shrinkage cracking properties of cement stone in which cement is substituted with glass waste finely ground powder. Drying shrinkage is defined as the time-dependent volume change induced by water loss in a specimen which is allowed to be dried due to exposure to an environment with certain relative humidity and temperature. The restraint of drying, autogenous or thermal shrinkage can result in the development of tensile residual stresses. Residual stresses develop over time since shrinkage occurs in response to moisture loss. If the residual stresses that develop are large enough, they may cause cracking of concrete. Crack occurrence time, crack development, crack width and free drying shrinkage strain all depend on physical and mechanical properties of cement and waste glass powder applied.

3. Experimental studies

Laboratory tests were carried out on cement paste specimens, in which waste glass powder (WGP) addition was used as a supplementary cementitious material (SCM) during a cooperation research between the Budapest University of Technology and Economics (BME), Department of Construction Materials and Engineering Geology and the Riga Technical University (RTU), Institute of Materials and Structures (IMS), Department of Building Materials and Products. Preliminary results on workability and compressive strength are introduced in [14].

3.1 Materials

Ordinary Portland cement CEM I 42.5 N was used provided by a Hungarian cement factory. Waste glass powders (WGPs) were prepared in RTU IMS laboratory directly for the present experiments, using waste glass cullet collected in Latvia. Five different WGPs were studied [14]. Fluorescent lamp tube glass waste cullet (LB) and incandescent light bulb borosilicate glass waste cullet (DRL) were received from a lamp recycling centre in Liepaja, Latvia. Container glass was obtained as bottles in green (G), amber (A) and flint (F) colours which were collected at a glass bottle return point in Riga, Latvia, and were manually crushed into cullet under laboratory conditions. The cullet was washed, dried and ground for 30 minutes in a laboratory planetary ball mill (Retsch PM400) with rotation speed 300 min^{-1}. The specific surface area of the WGP was obtained by a Zwick/Roell ToniPERM automatic Blaine apparatus (see *Table 1*).

DRL	LB	A	G	F	Cement
608	542	542	463	502	344

Table 1. Specific surface area of waste glass powders and Portland cement [m^2/kg]
1. táblázat A felhasznált hulladéküveg porok és portlandcement fajlagos felülete [m^2/kg]

The grading curves for the different waste glass powders are given in *Fig. 1.*

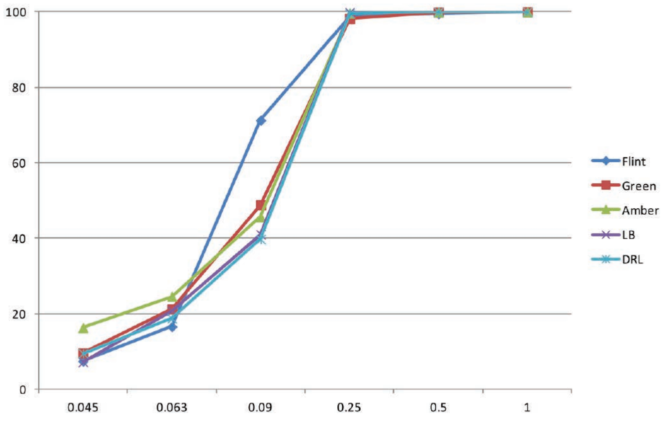

Fig. 1. The grading curves of the WGP materials
1. ábra A hulladéküveg porok szemcseméret eloszlása

3.2. Preparation of specimens

Portland cement was substituted with WGP at levels of 20% or 30% per mass of cement. The water/binder ratio was selected to be w/c = 0.285. Where cement substitution by WGP was applied, the water/cement ratio was changed to w/b = 0.342 (20% WGP) and w/b = 0.3705 (30% WGP), however, the water/binder ratio was kept constant at w/c=0.285. The components of the mortar mixture were batched by weight, cement and waste glass were premixed for 2 min, entire amount of water was added and mixed for 3 min, the mortar mixtures were mixed for an additional 5 min, resulting in a total mixing period of 10 min in a laboratory mortar mixer according to EN 196-1:2005 [15]. The workability of the fresh mortar was tested by flow table test according to EN 1015-3:1999 [16]. For all series, measured flow diameter results are given in [14].

3.3 Drying shrinkage test

The test method according to the Hungarian standard MSZ 523-5:1975 [17] was used for the drying shrinkage tests. Three 40 mm × 40 mm × 160 mm prismatic specimens were prepared for each series to the drying shrinkage tests. The specimens were removed from the moulds after 24 hours and the initial length of the specimens was measured. Specimens were stored in a climatic chamber at 20±2°C temperature and 65±5% relative humidity until the deformation measurements at 1, 2, 3, 6, 8, 9, 10, 13, 14, 15, 16, 17, 20, 21, 23, 27, 28, 30, 56, 91, 147, 282 and 592 days of age for specimens with soda-lime waste glass powder and at 1, 2, 3, 7, 8, 9, 10, 11, 14, 15, 17, 21, 22, 29, 57, 92, 148, 276 and 586 days for fluorescent lamp tube and incandescent light bulb borosilicate waste glass powder. The length changes were recorded using comparator Graaf-Kaufmann device according to the method detailed in the Hungarian standard MSZ 523-5:1975[17] *(Fig. 2)*

3.4. Early age shrinkage cracking test

Three ring specimens (see *Fig. 3*), for each series were prepared for measuring early age shrinkage cracking tendency. After 24 h, the outer steel ring moulds of specimens were removed. Then specimens were exposed to drying conditions at 20±2°C temperature and 65±5% relative humidity in a climatic chamber. Development of cracks was followed and cracking time was recorded for each ring specimen. Ring specimens were exposed to drying conditions from the outer and both the top and the bottom side of cement paste (see *Figs. 4* and *5*).

Fig. 2. Graaf-Kaufmann device with Mitutoyo comparator (minimum measurement interval 0.001 mm) with reference specimen
2. ábra Graf-Kaufmann készülék digitális Mitutoyo hosszváltozás-mérővel (felbontás 0,001 mm) és referencia etalonnal

Fig. 3. The preparation and testing of ring specimens for early age cracking tendency
3. ábra A korai zsugorodási repedésérzekenység vizsgálata gyűrű alakú próbatesteken

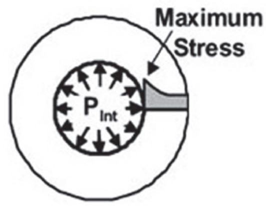

Fig. 4. Typical stress development of a restrained ring specimen [18]
4. ábra Jellegzetes feszültségeloszlás a gyűrű alakú próbatestben [18]

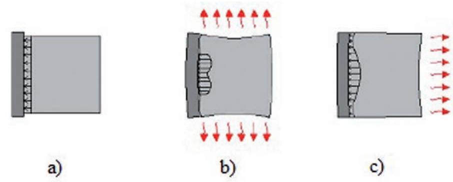

Fig. 5. Influence of drying shrinkage condition on the deformation of cement paste mortar and steel rings: a) uniform shrinkage, b) top and bottom drying, c) circumferential drying [18]
5. ábra A kiszáradás módjának hatása a gyűrű alakú próbatest deformációjára: a) egyenletes zsugorodás, b) alsó és felső oldali kiszáradás, c) palástirányú kiszáradás [18]

4. Results and discussions

4.1. Drying shrinkage

The time development of drying shrinkage values of the hardened cement paste specimens with WGP are indicated in *Figs. 6* and *7*.

As it can be seen on *Figs. 6* and *7* the drying shrinkage of mixtures with 30% of WGP content are higher than in case of 20% WGP content. It can be also realized from the results that almost all mixtures provide higher shrinkage than the reference mixture (that was made without WGP). Therefore, it can be concluded that WGP increases drying shrinkage of cement pastes, but it should be noted that the difference is not significant between the reference and the tested mixtures. It is supposed that the tested WGP of high specific surface area can be involved in the hydration of the cement paste. The highest shrinkage was recorded in case of series G2 (green colour) WGP, and the lowest shrinkage was recorded in case of series G3 (amber colour) by testing of both (20% and 30%) WGP contents.

As it can be seen in *Figs. 6* and *7*, the application of soda-lime waste glass powder as cement substitute does not influence negatively the drying shrinkage deformation of cement paste mortars in comparison to the reference specimens, during the period of 592 days (see *Table 2*). Shrinkage deformation is the highest at early age for the specimens with soda-lime WGP (flint colour) and particularly for green colour at 30% WGP content. At the same time, green colour WGP (20%), amber colour WGP (20% and 30%) specimens show smaller deformations; nearly equal to that of the reference cement paste specimens. Application of fluorescent lamp tube and incandescent light bulb borosilicate waste glass powder as cement substitute does not influence negatively the drying shrinkage deformation of cement paste mortars in comparison to the reference specimens, during the period of 586 days. The development of the deformations in specimens with WGP addition follows that of the reference cement paste specimens.

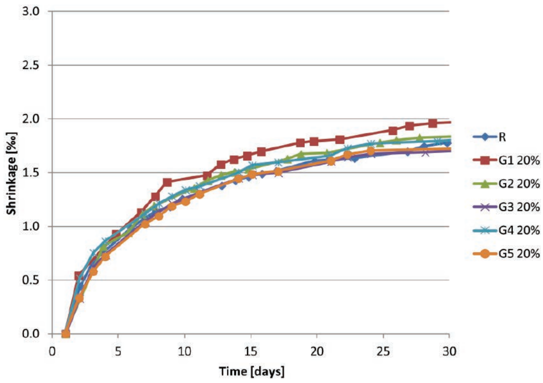

Fig. 6.a. Shrinkage of cement pastes with 20% WGP content
6.a ábra A 20% megőrölt hulladék üveg tartalmú próbatestek zsugorodása

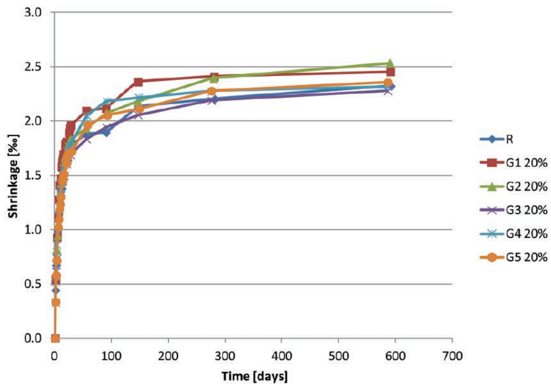

Fig. 6.b. Shrinkage of cement pastes with 20% WGP content
6.b ábra A 20% megőrölt hulladék üveg tartalmú próbatestek zsugorodása

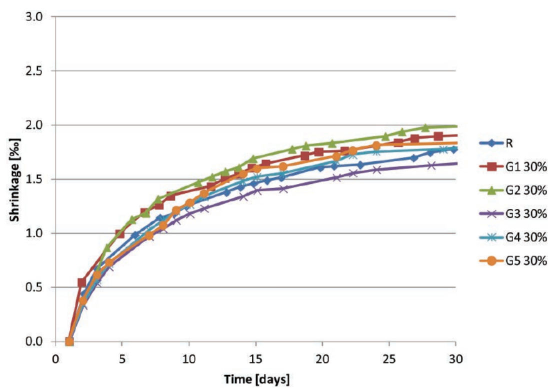

Fig. 7.a. Shrinkage of cement pastes with 30% WGP content
7.a ábra A 30% megőrölt hulladék üveg tartalmú próbatestek zsugorodása

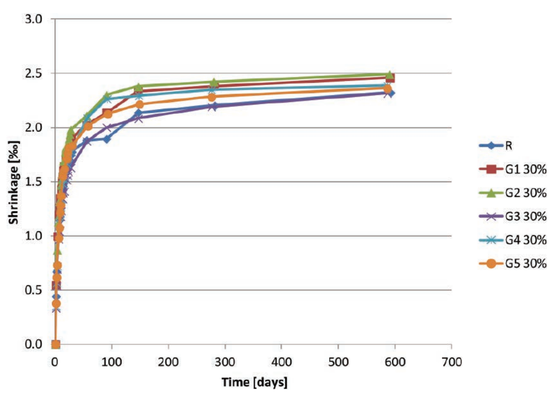

Fig. 7.b. Shrinkage of cement pastes with 30% WGP content
7.b ábra A 30% megőrölt hulladék üveg tartalmú próbatestek zsugorodása

Name	REF	F	G	A	LB	DRL
20%WGP	2.32	2.45	2.53	2.28	2.32	2.36
30%WGP		2.46	2.49	2.31	2.38	2.36

Table 2. Drying shrinkage values of the hardened cement paste specimens at 592 days [‰]
2. táblázat A zsugorodás végértéke 592 napos korban [‰]

Name	REF	F (G1)	G (G2)	A (G3)	LB (G4)	DRL (G5)
20% GLP	32,8	40.3	43.5	43.5	49.0	44.2
30% GLP		45.5	46.4	47.2	53.2	51.3

Table 3. Early age shrinkage cracking time values of the hardened cement paste specimens [hours]
3. táblázat Az első repedés megjelenéséhez tartozó időtartam gyűrűs vizsgálat során [óra]

4.2. Early age shrinkage cracking

Table 3 indicates cracking time values for all mixtures tested. The most important result is that the reference mixture had the shortest cracking time, so the early age shrinkage cracking tendencies of mixtures with WGP addition were found to be more favourable than that of the reference mixture. This observation is attributed to the slower setting of the mixtures with WGP addition. The use of LB type (G4) glass powder provided the longest cracking time; this WGP is considered to be the best in the point of view of early age shrinkage cracking tendency. The effectiveness of the other WGPs were – in decreasing order – G5, G3, G2, and finally G1, but the results are very close to each other, so the cracking tendencies can be considered as almost the same. The same observation can be made on effectiveness of the WGPs in case of both 20% and 30% substitution levels.

5. Conclusions

The present paper has summarised the experimental results of a laboratory test series carried out on cement paste mortar specimens, in which waste glass powder (WGP) addition was used as supplementary cementitious material (SCM) during a cooperation research between the Budapest University of Technology and Economics (BME), Department of Construction Materials and Engineering Geology and the Riga Technical University (RTU), Institute of Materials and Structures (IMS). CEM I 42.5 N Portland cement was used with WPG substitution at levels of 20% or 30% per mass of cement.

It was demonstrated that the WGP addition:

- For 20% and 30% per mass of cement seems to be applicable in view of drying shrinkage with total deformation up to 2.5 ‰ in the period of 592 days. The increase in waste glass powder addition leads to an increase in drying shrinkage.
- The highest shrinkage was recorded in case of series G2, green colour soda-lime WGP, and the lowest shrinkage was recorded in case of series G3, amber colour soda-lime WGP by testing of both (20% and 30%) WGP contents.

- The WGP addition contributes to a slowdown in the rate of hydration of the cement paste, so the early age shrinkage cracking tendency becomes more favourable, which can be seen in the longer cracking time result during the ring tests.
- In the point of view of early age shrinkage cracking tendency, the best performance was realized for series G4, fluorescent lamp tube WGP, at both 20% and 30% substitution levels. The other WGPs provided almost the same early age shrinkage cracking tendency, needed about 35% more time for the appearance of the first early age crack, compared to the reference cement paste.

6. Acknowledgement

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Megőrölt hulladék üveg (WGP) cement kiegészítő anyag (SCM) tulajdonságai – Száradási zsugorodás és korai zsugorodási repedésérzékenység

Az Európai Unió direktívái a csomagolóanyagok újrahasznosítására vonatkozóan is megfogalmaznak irányelveket, amelyek a tagállamok számára iránymutatásként szolgálnak. Jelen kutatás során lett-magyar közös kutatási projektben, a Rigai Műszaki Egyetem (RTU) és a Budapesti Műszaki és Gazdaságtudományi Egyetem (BME) kutatói tanulmányozták a hulladék üveg újrahasznosításának lehetőségét. Több eltérő, hulladéküveg alapanyagból készült, laboratóriumi körülmények között finomra őrölt üvegpor, cement kiegészítő anyagként történő felhasználási lehetőségét vizsgálták. A megőrölt hulladék üvegpor adagolásának mennyisége 20% és 30% volt a cement tömegére vonatkoztatva. A cikkben a száradási zsugorodás mértéke és a korai zsugorodási repedésérzékenység bemutatása történt meg, megszilárdult cementkő próbatestek laboratóriumi vizsgálatát követően. Sikerült igazolni, hogy a száradási zsugorodás szempontjából a megőrölt hulladék üvegpor alkalmazása nem kedvezőtlen, a vizsgált adagolások esetén. A zsugorodás mértéke 2,5 ‰, 592 napos korban. A korai zsugorodásból származó repedésérzékenységet a megőrölt hulladék üvegpor adagolása kedvezően befolyásolja; a gátolt zsugorodásból származó első repedés kialakulása későbbi időpontban következik be, mint a cement kiegészítő anyagot nem tartalmazó referencia keverék esetén.

Kulcsszavak: újrahasznosítás, hulladék üveg, cement kiegészítő anyag, száradási zsugorodás, korai zsugorodási repedésérzékenység