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CROW-CUR Recommendation 128:2021
MSWI filler in unreinforced earth-moist concrete

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CROW-CUR Recommendation 128:2021

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Introduction

In recent years, demand for appropriate concrete filler materials – particularly those with a pozzolan character – has increased. One of the products capable of filling this gap in the market is MSWI filler, which is made from bottom ash sourced from municipal solid waste incinerators (MSWIs). In addition to the standard processing steps applied to this bottom ash, the production of MSWI filler involves a specific wet milling process. This filler is also a useful way to repurpose a mineral residual material.
In this CROW-CUR Recommendation, the use of MSWI filler in concrete is limited to unreinforced concrete products made with earth-moist concrete, such as concrete paving slabs, concrete tiles, and concrete curbs. By compiling this CROW-CUR Recommendation, which sets out the quality requirements for MSWI filler, the product can be included as a new type of raw material in the Dutch Assessment Guideline BRL 1804, "Fillers for use in concrete and mortar".
When supplied as part of a certified BRL 1804 process, this filler can be used with confidence as a type I filler in unreinforced concrete products made with earth-moist concrete.

The Dutch Concrete Agreement sets out a national ambition to make the concrete chain more sustainable. One of its goals is the 100% high-quality reuse of residual concrete waste. The use of MSWI filler has therefore also been checked for circularity and environmental performance in line with the Dutch Soil Quality Decree; this work falls outside the scope of this CROW-CUR Recommendation, but has been coordinated with the members of this CROW working group. Concrete granulate made from concrete with MSWI filler has been compared with a reference material of concrete granulate made only with primary raw materials. The comparison looked at engineering and environmental aspects as well as circularity. This comparison shows that concrete granulate and filler recycled from concrete rubble with MSWI filler can be responsibly reused as a raw material in concrete.

The contents of this CROW-CUR Recommendation are based on the results obtained from an extensive trial of concrete made with MSWI fillers, which have been recorded in a background report.

This CROW-CUR Recommendation has been drafted by the CROW working group 'MSWI filler in unreinforced concrete'. At the time of publication of the recommendation, the working group comprised:

Angelo Sarabèr *(Sarabèr Consultancy, chairman)*
Angelo Antoniadis *(Kiwa)*
Erwin Bakker *(Blue Phoenix Group)*
Rob Bleijerveld *(Mineralz)*
Eugene Caron *(Master Builders Solutions Nederland)*
Mark van Kempen *(Blue Phoenix Group)*
Felix Leenders *(Mobilis)*
Erik Onstenk *(Pelt & Hooykaas)*
Math Pluis (Betonhuis)
Jos van der Scheer *(Kijlstra Betonwaren)*
Evert Schut *(RWS)*
Henk Soen *(Blue Phoenix Group)*
Ludwig Temme *(Gemeente Amersfoort)*
Edwin Vermeulen *(Betonhuis)*
Martin Verweij *(Cementbouw)*
Gert van der Wegen *(SGS INTRON, author)*

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The contents of CROW-CUR Recommendation 128 were shared prior to release with the members of the NEN standards committee 353 039 'Concrete' and its 'Fillers' working group. The responses and comments obtained have, as far as possible, been incorporated into this recommendation.

Contents

1 Subject and scope

1.1 Subject

This CROW-CUR Recommendation sets out definitions, requirements, and rules for MSWI filler, which is produced using MSWI bottom ash obtained from a municipal solid waste incinerator with a wet slag remover whereby, in addition to the standard processing steps performed on bottom ash – namely sieving and the removal of ferrous and non-ferrous metals – a wet milling process is also carried out. MSWI filler must be produced from the full spectrum of grades of MSWI bottom ash.

1.2 Scope

This CROW-CUR Recommendation applies to MSWI filler used in unreinforced, non-construction concrete products made with wet concrete mortar in a consistency class of C0 (dry) or C1 (earth-moist) and with a maximum MSWI filler content of 140 kg/m^3.

2 Terms and definitions

MSWI bottom ash

MSWI bottom ash is created when domestic waste and equivalent commercial waste materials (including biomass) are combusted in a municipal solid waste incinerator (MSWI) with a grate incinerator. Bottom ash from biomass energy plants may comprise up to 5.0% m/m of the MSWI bottom ash, as long as it comes from a biomass energy plant located within the same facility and is added to the unprocessed MSWI bottom ash. Boiler ash may form part of the MSWI bottom ash as long as the boiler ash is produced together with the MSWI bottom ash and is added during the combustion process itself.

MSWI filler

The filler produced from MSWI bottom ash, originating from a MSWI with a wet slag remover whereby, in addition to the standard processing steps performed on bottom ash, a wet milling process is also carried out.

3 Material requirements

MSWI filler must meet the requirements set out in the table below.

Property	Method	Requirement
Particle distribution	NEN-EN 933-10	100% < 2 mm 85–100% < 125 µm 70–100% < 63 µm
Alkali content, expressed as Na_2O equivalent	X-ray fluorescence spectrometry (XRF) NEN-EN 196-2	≤ 5.0%(m/m) 1)
Methylene blue adsorption	NEN-EN 933-9	≤ 1.2% (m/m)
Chloride content	NEN-EN 196-2	≤ 1.0%(m/m) 2)
Sulfate content – SO_3	NEN-EN 196-2	≤ 4.0%(m/m) 3)
Effect on strength 4,5)	NEN-EN 196-1	≥ 65%
Effect on setting time 4)	NEN-EN 196-3	< 120 minutes
Determination of soundness 6)	NEN-EN 196-3	< 10 mm
TOC content	NEN-EN 13639	≤ 6% (m/m)
Metallic Al + Zn content	CUR Recommendation 116	≤ 0.2% (m/m)

1) If the XRF value is > 5% (m/m), this value must be determined as an alkaline-soluble alkali content in accordance with NEN-EN 196-2, whereby the digestion of the sample MSWI filler takes place in accordance with 4.4.4.2 but with a solution of 107 g LiOH per 1000 ml instead of the described KOH solution.
2) This requirement applies at 25% (m/m) replacement of cement with MSWI filler. For higher replacement percentages, the limit value is reduced proportionately.
3) If the acid-soluble sulfate content, expressed as SO_3, is 0.2 ≤ x ≤ 4.0% (m/m), the sulfate content in the aggregate used must not exceed 0.2% (m/m) (AS0.2) and this limit on the use of aggregates must be included in the product specifications. Fillers with a sulfate content, expressed as SO_3, in excess of 4.0% (m/m) must not be used.
4) Requirement applies to mixtures of 25% (m/m) filler and 75% (m/m) CEM I 42.5 compared to test specimens made with 100% CEM I 42.5.
5) If the air content of the mortar with MSWI filler is higher than that of the reference mortar, the compressive strength of the reference mortar must be reduced by 5% for each % of higher air content before conducting the test. This correction was introduced because MSWI filler can result in an increased air content in plastic mortars; this does not occur in dry and earth-moist mortars.
6) Requirement applies to mixtures of 25% (m/m) filler and 75% (m/m) CEM I 42.5.

Titles of standards and documents referenced	
NEN-EN 196-1	Methods of testing cement – Part 1: Determination of strength
NEN-EN 196-2	Methods of testing cement – Part 2: Chemical analysis of cement
NEN-EN 196-3	Methods of testing cement – Part 3: Determination of setting times and soundness
NEN-EN 933-9 NEN-EN 933-9	Tests for geometrical properties of aggregates – Part 9: Assessment of fines – Methylene blue test
NEN-EN 13639	Determination of total organic carbon in limestone
CUR Recommendation 116	MSWI Granulate as an Aggregate for Concrete
Background Report for CROW-CUR Recommendation 128	'A Study on the Suitability of Ground MSWI Bottom Ash as a Filler in Unreinforced Earth-Moist Concrete', SGS INTRON report A117460/R20210149, July 2021

Appendix
Background report for CROW-CUR Recommendation 128:2021

A study on the suitability of wet-ground MSWI bottom ash as a filler in unreinforced earth-moist concrete

SGS INTRON B.V. report

Contents

Summary

Introduction
MSWI bottom ash can be processed and wet-milled to produce a filler for use in unreinforced, earth-moist concrete. To use this MSWI filler in a responsible and accepted way in concrete, an assessment system is required in the form of a CROW-CUR Recommendation.
This Recommendation also forms the technical basis for the inclusion of this type of filler in Assessment Guideline BRL 1804, which can be used to certify the filler.
An extensive characterization and concrete study was conducted to map out the properties and performance of MSWI filler. This study also looked at the circularity of concrete in which MSWI filler is used. These insights were used as the basis for the CROW-CUR Recommendation.

The results of the study are set out in this report, which serves as a background document to the relevant CROW-CUR Recommendation.
The study was designed and conducted under the supervision of CROW working group N1794, 'MSWI filler in unreinforced concrete'.

Activities undertaken
Representative samples of MSWI filler were characterized in terms of their relevant properties for use in concrete. The study also looked at the effect of the MSWI filler on the key performance criteria for factory-produced concrete tiles, using concrete tiles without filler and concrete tiles with ground limestone as a filler as references.
To assess the effect of MSWI filler on the circularity of concrete, concrete granules with MSWI filler were characterized, and concrete made with these granules was examined in terms of its basic properties, both technological and environmental. The study also looked at the question of whether hardened cement with MSWI filler could potentially be ground up and reused as a filler in new concrete.

Conclusions
Based on the studies conducted, we can conclude that the MSWI filler under consideration is suitable for use in unreinforced, non-construction concrete products made with dry or earth-moist concrete mortar.
The study also showed that, when MSWI filler is used in these products, the material streams generated when the concrete in question is recycled (concrete granulate and powder fraction) can be reused as a raw material in a 2nd life concrete. This application of MSWI filler is therefore fully circular in terms of the aspects within the scope of this study.

Recommendations
Alongside the generic properties listed in BRL 1804, we recommend incorporating the following aspects for MSWI filler into the CROW-CUR Recommendation:
- Alkali content (Na_2O-eq)
- TOC content
- Metallic Al + Zn content
- Chloride content

1 Introduction

Blue Phoenix Group (BPG) wishes to market MSWI filler as a certified filler for use in unreinforced concrete products made with earth-moist concrete mortar. This MSWI filler is made from MSWI bottom ash in a process which, in addition to the standard processing steps performed on bottom ash – namely sieving and the removal of ferrous and non-ferrous metals – also involves a wet milling process. The product is supplied as a powder filler.

To certify this MSWI filler in accordance with BRL 1804, a CROW-CUR Recommendation must first be drawn up to form the technical basis for this certification. The studies required for this purpose were determined by the CROW working group N1794 'MSWI filler in unreinforced concrete'. The research also looked at the circularity of concrete in which MSWI filler is used.

This report, which serves as a background report to the CROW-CUR Recommendation, sets out the results of the conducted studies. The decisions made in relation to specific aspects, such as those included in the CROW-CUR Recommendation, are also explained in further detail.

2 Study design

The study was conducted on three samples of MSWI filler. According to Blue Phoenix Group, the material used to produce these samples originated in three different municipal solid waste incinerators (MSWIs) in the Netherlands and is representative of MSWI bottom ash generated in the Netherlands (see appendix A). This appendix also includes information on how the MSWI bottom ash samples were obtained and the process used to turn them into MSWI filler.

The study program is divided into multiple sections:
- Characterization of the three samples of MSWI filler
- Effect of filler on paste and mortar properties
- Technological study of the concrete product in which MSWI filler was used ('1st life')
- Study of 2nd life (circularity), including technological and environmental factors.

Based on the results obtained in the first two sections of the program, one MSWI filler was selected for a full-spectrum study in the subsequent two sections.

2.1 Characterization of MSWI fillers

The following properties were determined for each of the three samples of MSWI filler:
- Particle distribution (laser granulometry)
- Water requirement $ß_p$ value: appendix C of BRL 1804
- Chloride content (acid- and water-soluble): NEN-EN 196-2 and NEN-EN 1744-1 respectively
- Sulfate content (acid- and water-soluble): NEN-EN 196- and NEN-EN 1744-1 respectively
- Alkali content (Na_2O-eq): NEN-EN 196-2
- Water-soluble phosphate content: appendix C of NEN-EN 450-1
- Organic compounds content (TOC): NEN-EN 13639
- Metallic Al + Zn content: appendix A of CUR Recommendation 116
- Element composition with X-ray fluorescence spectroscopy (XRF): NEN-EN 196-2
- Mineral composition: quantitative X-ray diffraction patterns (XRD)
- Microstructure/composition: scanning electron microscopy (SEM) + element analysis (EDXA)

A summary specification of the XRF and XRD measuring method is provided in appendix B.

2.2 Paste and mortar tests

Paste and mortar tests were conducted using the three samples of MSWI filler and a widely available ground limestone (as a reference), with 25% (m/m) of the cement replaced with these fillers. As an additional reference, these tests were also conducted on pastes and mortars without filler (100% cement). The standard-compliant pastes and mortars were mixed according to NEN-EN 196-3 and NEN-EN 196-1, using CEM I 52.5 N as a binding agent (ENCI Maastricht). CEM I 52.5 N was selected because this cement is used to produce the concrete tiles used in the concrete study.

The following properties were determined:
- Air content (fresh mortar) in accordance with NEN-EN 12350-7
- Setting time (paste) in accordance with NEN-EN 196-3
- Soundness (Le Chatelier) in accordance with NEN-EN 196-3
- Autoclave test (on paste) in accordance with ASTM C151
- Expansion when stored under water at 40°C. At the end of the test, a micro section was examined under a microscope
- Compressive strength after 7, 28, and 90 days of hardening in accordance with NEN-EN 196-1

The effect of MSWI filler on the alkali-silica reaction (ASR) was studied using the Ultra-Accelerated Mortar Bar Test (UAMBT) in accordance with appendix E of CUR Recommendation 89 with the following combinations:

- CEM I 52.5 without MSWI filler in combination with both reactive and non-reactive aggregate (two references)
- The MSWI filler selected in the previous steps, which replaces 25% m/m of the cement, in combination with both reactive and non-reactive aggregate
- Both of the other MSWI fillers (replacing 25% (m/m) of the cement) in combination with reactive aggregate only

As no reactive aggregate was available, we opted to use borosilicate glass as an alkali-reactive material. Glass beads made from this material were crushed and sieved into the required particle fractions for the UAMBT test. To obtain substantial expansions, test specimens measuring 25 x 25 x 285 mm were used in this test.

2.3 Concrete study: 1st life

In the original design, this study was to be carried out on concrete paving slabs pressed in the laboratory, with a formula and compression compressive used in real-life applications. However, as the intense compression energy could not be replicated in the laboratory, the concrete paving slabs produced in the laboratory had a splitting resistance/tensile strength of just half of the normal expected value. For this reason, in consultation with the CROW working group, we decided to have the test specimens produced by a specialist company outside of the laboratory, with Blue Phoenix Group and SGS INTRON managing the project. SGS INTRON employee and engineer Bianca Baetens supervised and documented the entire production process. Appendix C lists the key details of the production process.

Five series of concrete tiles were produced:

- Concrete without filler (reference 1), produced in the standard way
- Concrete with ground limestone as a filler (reference 2)
- Concrete with the three samples of MSWI filler

The four fillers were dosed to replace 25% (m/m) of the cement.

After 28 days of hardening at 20°C and with their own moisture content unaltered, the following properties were determined in three-fold for each of the concrete tiles:

- Volumetric weight in accordance with NEN-EN 12390-7
- Dynamic e-modulus (calculated from ultrasonic propagation velocity)
- Compressive strength of removed cube-shaped sample in accordance with NEN-EN 12390-3
- Flexural strength in accordance with appendix F of NEN-EN 1339
- Road salt resistance in accordance with appendix D of NEN-EN 1339
- Capillary water absorption and drying

2.4 Circularity

Another CROW working group is currently putting together a system for assessing the suitability of raw materials for circular concrete. As this system had not yet been published when this study commenced, it was not possible to investigate all aspects, including substances of very high concern (SVHC) and radioactivity. The technological and environmental aspects listed below were investigated as part of the study.

2.4.1 Technological: Concrete granulate

A number of concrete tiles made from three of the concrete mixtures were subjected to a two-month period of rapid hardening in water at a temperature of 40°C after their initial 28-day hardening period at 20°C, with the aim of achieving a higher level of hydration (to replicate 'old' concrete). These concrete tiles were then broken up in a jaw crusher and dry-sieved into concrete granulate measuring 4–22 mm. This step was carried out on the concrete mixture without filler (reference 1), the concrete mixture with ground limestone as a filler (reference 2), and the concrete mixture with the MSWI filler selected during the first stage of the study.

These three coarse concrete granulates were then subjected to the following tests:

- Characterization:
  - (Particle) density and water absorption in accordance with NEN-EN 1097-6
  - Particle distribution in accordance with NEN-EN 933-1
- Production of plastic concrete (S3) with 320 kg/m^3 CEM I 42.5 N and wcf 0.50, and determination of:
  - Compressive strength after 7 and 28 days in accordance with NEN-EN 12390-3
  - Water penetration after 28 days of hardening in accordance with NEN-EN 12390-8
  - Chloride migration coefficient after 28 days of hardening in accordance with NT Build 492

2.4.2 Technological: Filler

Using innovative recycling techniques, most of the cement can be separated from the aggregate, which means that this powder fraction may be suitable for reuse as a filler in new concrete. To determine the effect of MSWI filler on the quality of a 2nd life filler, the following test was carried out:

Three cement pastes were produced with a water-binding factor (wbf) of 0.35 (comparable to that of the concrete tiles): one cement paste with no filler (reference 1), one cement paste with ground limestone as a filler (reference 2), and one cement paste with the MSWI filler selected during the first stage of the study. These cement pastes were subjected to a two-month period of rapid hardening in water at a temperature of 40°C after their initial 28-day hardening period at 20°C, with the aim of achieving a higher level of hydration (to replicate 'old' concrete). After this rapid hardening phase, the specimens were broken up in a jaw crusher to achieve a particle size of < 4 mm, and then dry-milled for one hour in a ball mill to achieve a powder consistency.

The three '2nd life' fillers produced using this method were tested for the following properties:

- Effect on setting time in accordance with NEN-EN 196-3
- Soundness in accordance with NEN-EN 196-3
- Compressive strength after 7 and 28 days in accordance with NEN-EN 196-1

2.4.3 Environmental

After 28 days of hardening at 20°C and with their own moisture content unaltered (hermetically sealed in plastic film), only the concrete tiles produced without a filler (reference 1) and those with the selected
MSWI filler were broken up into particle sizes of < 4 mm. Both of these concrete granulate samples were tested for leaching using a column test in accordance with NEN 7383.

3 Results and analysis

3.1 Characterization of MSWI fillers

For the study, BPG delivered three samples of MSWI filler to the SGS INTRON laboratory in Sittard in the Netherlands. BPG deliberately produced these samples with a certain degree of variation, including different TOC levels, to illustrate the effect of these differences on the properties of the mortar and concrete (mortar).

3.1.1 Chemical analyses and water requirements

Table 1 lists the results of the chemical analyses and water requirement tests.

Table 1. Characterization of MSWI fillers

Property	Unit	MSWI-1	MSWI-2	MSWI-3	Generic requirement in BRL 1804
Insoluble (HCl/Na_2CO_3)	% (m/m)	41.7	43.5	44.1	-
Sulfate, water-soluble (SO_3)	% (m/m)	1.18	0.70	0.88	-
Sulfate, acid-soluble (SO_3)	% (m/m)	2.10	1.31	1.65	≤ 4.0
Chloride, water-soluble	% (m/m)	0.19	0.11	0.29	-
Chloride, acid-soluble	% (m/m)	0.32	0.23	0.42	-
Alkali-equivalent, XRF	% (m/m)	4.8	4.8	4.6	≤ 5.0
Soluble phosphate (P_2O_5)	% (m/m)	< 0.0010	< 0.0010	< 0.0010	-
Metallic aluminum + zinc	% (m/m)	< 0.03	< 0.03	< 0.03	-
TOC	% (m/m)	5.8	2.0	0.69	-
Water requirement, $ß_p$ value	V/V	1.54	1.18	1.32	-

The sulfate content is lower than the generic requirement set in BRL 1804 (≤ 4.0% (m/m)) and the requirement set in EN 450-1 for fly ash (≤ 3.0% (m/m)).

BRL 1804 does not specify a generic requirement for chloride content because a maximum chloride content limit is in place for concrete mortar used in reinforced and prestressed concrete due to the risk of reinforcement corrosion. The total chloride content across all of the raw materials used must satisfy this criterion. As the applications of MSWI fillers are limited to unreinforced concrete, this maximum chloride content limit is not relevant. A further reason to limit the chloride content is its impact on the shrinkage characteristic of the concrete. This impact is only noticeable at high chloride levels (> 1% (m/m) of the cement weight). Even at very high doses of MSWI filler – for example 50% of the cement weight – the effect on chloride content is limited to 0.2% (m/m) of the cement, which will not have a negative impact.

The alkali equivalent was determined using XRF, which measures the total content including the alkalis present in the amorphous fraction (glass) of the MSWI fillers. Although these alkalis are only released when this glass has been (partially) dissolved by pozzolan reactions, the measured values satisfy the generic requirement set in BRL 1804 (≤ 5.0% (m/m)).

The water-soluble phosphate and metallic aluminum + zinc content are below the lower limit value set in the prescribed measurement methods and are therefore effectively absent. There are no generic requirements for these two aspects in BRL 1804. In terms of water-soluble phosphate, a requirement of < 0.01% (m/m) is set in NEN-EN 450-1 for fly ash and in BRL 1804 for filler released during the thermal cleaning of both tar-free and tar-containing asphalt. The water-soluble phosphate is therefore at least ten times lower than this requirement.

The TOC value (deliberately) varies significantly between the different MSWI fillers. For all three tested MSWI fillers, the value is above the supplementary requirement set for ground limestone in BRL 1804 ($\leq$ 0.5% (m/m)).
Concrete produced using ground limestone with a TOC content above 0.5% (m/m) appears to be sensitive to road salt. This aspect was investigated further for the MSWI fillers (see section 3.3).

The $ß_p$ value of the three tested MSWI fillers is higher than that of cement (CEM I 52.5 = approx. 1.2) and other fillers such as fly ash (approx. 0.7) and ground limestone (approx. 0.8).
This means that plastic mortar and concrete mortar with MSWI fillers require more water.

The determination of methylene blue adsorption was not part of the characterization tests described above. Tests performed on three samples of MSWI filler of the same origins as MSWI-3 but taken over a period of a number of months in 2018 resulted in a methylene blue adsorption value of 0.16% (m/m) [SGS INTRON report A101790/ R20180428c dated 12-7-2018]. This value is significantly lower than the requirement of < 1.2% (m/m) set in BRL 1804.

3.1.2 Particle distribution

The particle distribution of the three tested MSWI fillers and the particle distribution of the CEM I 52.5 N and ground limestone mixture used in the production of the concrete tiles, measured using laser granulometry, is shown in the graphs in appendix D. The characteristic particle dimensions are listed in table 2.

Table 2. Characteristic particle distribution

Particle property	MSWI-1	MSWI-2	MSWI-3	Ground lime-stone	CEM I 52.5 N
d10 (µm)	0.51	0.46	0.24	0.84	0.79
d50 (µm)	8.4	8.2	5.8	9.8	7.6
d90 (µm)	47	55	25	48	34

Table 2 shows that sample MSWI-3 is somewhat finer than the other two tested samples of MSWI filler, which are virtually identical. The particle distribution of the four fillers and the cement are comparable. The particle distribution of the three MSWI fillers satisfies the requirements set in BRL 1804.

3.1.3 Elementary composition

The results of the elementary composition obtained using X-ray fluorescence (XRF) are shown in table 3. The variation between the three samples of MSWI filler is very low.
The main components (expressed as oxides) are silicon, calcium, iron, and aluminum (approx. 85% of the total). The sulfate content is in line with the wet chemical analysis.

3.1.4 Mineralogical composition

The mineralogical composition of the three tested samples of MSWI filler is shown in table 4.
The X-ray diffraction patterns are shown in appendix E.
The samples all have the same mineralogical composition with just slight variation in content levels.
They all contain a relatively large amount of amorphous material (approx. 66%). The main minerals encountered are quartz (approx. 14%), melilite-type minerals (approx. 6%) and calcite (approx. 4%).

Table 3. Elementary composition (% (m/m) as oxides)

Element (as oxide)	**MSWI-1**	**MSWI-2**	**MSWI-3**
Silicon as SiO_2	50.07	47.61	50.46
Calcium as CaO	18.18	17.03	16.41
Iron as Fe_2O_3	7.90	11.04	10.59
Aluminum as Al_2O_3	7.43	8.23	7.98
Sodium as Na_2O	4.13	4.13	3.94
Sulfur as SO_3	2.69	1.60	1.64
Magnesium as MgO	2.39	2.42	2.02
Phosphorus as P_2O_5	1.10	1.23	0.94
Titanium as TiO_2	1.15	1.32	0.98
Potassium as K_2O	1.01	0.97	1.02
Zinc as ZnO	0.54	0.60	0.50
Copper as CuO	0.31	0.38	0.27
Manganese as Mn_3O_4	0.16	0.21	0.18
Lead as PbO	0.11	0.11	0.11
Chromium as Cr_2O_3	0.10	0.11	0.09
Zirconium as ZrO_2	0.14	0.06	0.07
Barium as BaO	0.21	0.27	0.20
Strontium as SrO	0.07	0.05	0.05
Nickel as NiO	0.02	0.03	0.03
Vanadium as V_2O_5	0.01	0.01	0.01

Table 4. Mineralogical composition (202621-1 = MSWI-1; 202621-2 = MSWI-2; 202621-3 = MSWI-3)

Mineral	Theoretical formula[2]	202621-1	202621-2	202621-3
Silicates				
Quartz	SiO_2	14.8	11.3	15.6
Cristobalite	SiO_2	0.2	0.2	0.1
Alkali feldspar	$(NA,K)AlSi_3O_8$	0.6	0.5	0.9
Plagioclase/albite	$(Ca,Na)(Al,Si)_4O_8$	1.0	1.1	1.1
Melilite-type minerals	$(Ca,Na)(Al,Mg,Fe)(Si,Al)_2O_7$	5.0	6.5	5.9
Petedunnite	$Ca(Zn,Mn,Fe,Mg)Si_2O_6$	1.2	1.7	2.0
C_2S*, larnite	Ca_2SiO_4	1.2	0.1	0.5
Muscovite/mica	$(K,Ca,Na)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$	1.2	0.9	1.1
Carbonates				
Calcite	$CaCO_3$	4.5	4.8	3.1
Sulfates				
Bassanite	$CaSO_4 \bullet 1/2H_2O$	0.6	0.7	1.1
Anhydrite	$CaSO_4$	0.3	0.1	0.1
Oxides/hydroxides				
Magnetite	Fe_3O_4	1.6	2.4	2.2
Hematite	Fe_2O_3	0.8	1.0	0.7
Periclase	MgO	0.2	0.1	0.1
Wüstite	FeO	0.5	0.9	1.0
Rutile	TiO_2	0.3	2.1	0.1
Phosphates				
Apatite	$Ca_5(PO_4)_3(F,OH,Cl)$	0.8	0.9	0.5
Others/amorphous		**66.3**	**66.6**	**65.8**

3.1.5 Microstructure and composition

A scanning electron microscope (SEM) was used to examine the morphology and typical composition of the MSWI particles. The results obtained are described in detail in appendix F. The results indicate that the three tested samples of MSWI fillers display many similarities both in terms of their morphology and their typical composition. Figure 1 provides an overview of the typical particle shapes and sizes..

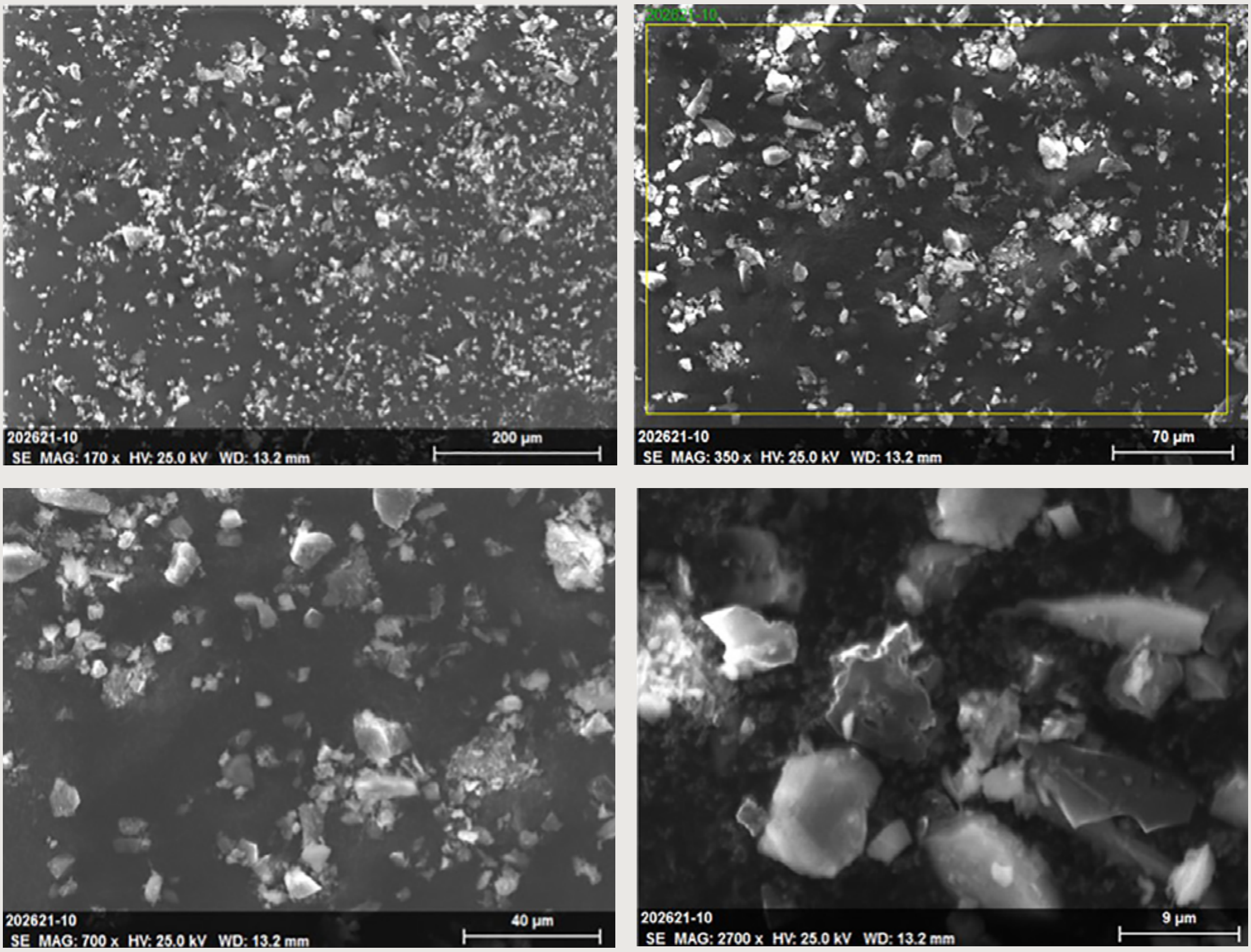


Figure 1. Typical particle shapes and sizes for the three MSWI fillers

3.1.6 Characterization conclusions

In spite of the differing origins of the MSWI bottom ash used as the raw material for the milling process, the MSWI fillers produced from these materials show only minor variations for the properties tested, with the exception of the TOC content, which was deliberately varied.
MSWI filler is made up of approximately two-thirds amorphous material. The mineral components are primarily quartz, a melilite-type silicate, and calcite.
The chemical and mineralogical analyses did not highlight any components (in significant amounts) that could prevent these MSWI fillers from being used in concrete.

3.2 Paste and mortar tests

3.2.1 Paste tests

The results of the paste tests, in which 25% m/m of the cement was replaced with filler, are summarized in table 5.

Table 5. Results of paste tests

Property	REF	GL	MSWI-1	MSWI-2	MSWI-3
Water requirement (% (m/m))	27.2	26.0	31.6	29.0	30.4
Start of setting (min.) *Variation from REF*	110	120 + 10	230 + 120	175 + 65	125 + 15
End of setting (min.) *Variation from REF*	150	190 + 40	310 + 160	265 + 115	200 +50
Soundness (mm)	0.5	0.0	0.0	0.0	0 ,5
Autoclave: Water content (% (m/m)) Meas. expansion (%)	 24.9 0.031	 23.5 0.015	 28.8 0.055	 26.9 0.044	 27.5 0.051

This table shows that the MSWI fillers require more water and slow down the rate at which the pastes set. A higher water content and the partial replacement of cement usually results in slower setting (due to the greater distance between the cement particles). However, the slowing effect of MSWI filler also seems to be related to its TOC content. The slowing effect is reduced in the following sequence: MSWI-1 (5.8%) ⟶ MSWI-2 (2.0%) ⟶ MSWI-3 (0.69%). The MSWI-3 filler has a comparable setting time to paste with ground limestone (GL).
The three MSWI fillers satisfy the requirement set in BRL 1804 (maximum 120-minute delay before start of setting); the delay time for MSWI-1 is exactly 120 minutes.

The soundness (Le Chatelier) of all five pastes is excellent, and there is very little to no expansion. Autoclave expansion is higher for the pastes with MSWI filler than for both of the reference pastes but is still comfortably within the required values set in ASTM C1157-20 (< 0.80%) and BRL 1804 (< 0.40%).

3.2.2 Mortar tests: Strength

The cement and ground limestone (GL) used in the mortar tests was the same as that used in the production of the concrete tiles. The mortar composition conforms to NEN-EN 196-1, with 25% m/m of the cement replaced with the relevant fillers. The results of the mortar test are summarized in table 6.

This table shows that the plastic mortars with MSWI fillers have a very high air content, which results in a low density. The differences in air content are by far the most significant cause of the large differences in the densities of the hardened mortars.
The difference in density between ground limestone and MSWI filler (2.7 and 2.5 kg/dm3 respectively) results in a difference of a maximum of 10 kg/m^3 in the density of the hardened mortars. This difference in air content means that the compressive strengths of the mortars with MSWI fillers are relatively low (60–80% of the reference mortar). However, if we correct the values for the difference in air content (bottom row of table 6), then the 28-day compressive strength of the three mortars with MSWI filler is approximately 90% of the reference mortar, while the value for the mortar with ground limestone is just 70% of the reference value. This indicates that the MSWI fillers make an additional contribution to the final strength of the mortar.

When MSWI fillers are used in earth-moist concrete mortars, there does not seem to be any increase in air content (see section 3.3). The cause of the increased air content in the plastic mortars with MSWI fillers was further investigated in a ‘foam test’ (see appendix G). Mixing (vigorously stirring with a glass rod) the MSWI filler with water creates a layer of air bubbles on the water. This indicates that there are surface-active components in the MSWI filler.
These air bubbles could not have been created as a result of hydrogen as forming from metallic aluminum, as no metallic aluminum was detected in the characterization of the MSWI fillers and this foam test was not conducted in an alkaline environment (demineralized water: neutral pH).

Table 6. Results of mortar tests

Property	Reference	GL	MSWI-1	MSWI-2	MSWI-3
Mortar:					
Density (kg/m^3)	2,219	2,229	2,058	2,041	2,149
Air content (%V/V)	4.0	2.9	10.0	11.5	6.8
Compressive strength (MPa):					
7 days	49.8 (100%)	35.9 (72%)	30.5 (61%)	28.7 (58%)	38.4 (77%)
28 days	66.2 (100%)	47.7 (72%)	40.7 (61%)	38.8 (59%)	49.2 (74%)
90 days	71.4 (100%)	54.3 (76%)	48.4 (68%)	45.4 (64%)	57.7 (81%)
Flexural strength (MPa):					
7 days	7.7 (100%)	6.2 (81%)	5.2 (68%)	4.9 (64%)	5.8 (75%)
28 days	8.6 (100%)	7.8 (91%)	6.1 (71%)	6.0 (70%)	6.6 (77%)
Density (kg/m^3):					
7 days	2,264	2,261	2,073	2,075	2,171
28 days	2,294	2,280	2,089	2,103	2,189
Compressive strength 28d (MPa) With correction to 4% air (1% air = 5% strength)	66.2 (100%)	45.1 (68%)	58.1 (88%)	62.1 (94%)	57.2 (86%)

3.2.3 Mortar tests: Expansion in water at 40°C

For this expansion test, three prisms (40 x 40 x 160 mm) were produced for each mixture in accordance with NEN-EN 196-1, at a temperature of 20°C. In the mixtures with filler, 25% (m/m) of the cement was replaced with the relevant filler. After production, the prisms were covered with a glass sheet for 23.5 hours. They were then removed from the mold for preparation of the measuring points. Throughout the process, the prisms were prevented from drying out. The first length measurement (0 measurement) was taken 24 hours after production at 20°C and was mathematically corrected to 40°C with an expansion coefficient of 13.10-6°C-1. The prisms were then stored under water at a temperature of 40°C for the remaining length measurements. In addition to the length, the weight of each prism was also checked. The average expansions and weight increases for the tested mixtures are shown in figure 2.
After six weeks, expansion continues to increase only very slightly or does not increase any further at all. Expansion in the mixtures with MSWI filler is at the same level as in the reference mixture without filler, so we can conclude that there are no longer any expansion mechanisms active at this point.
The amount of expansion and the weight increase caused by water absorption in the mortars with MSWI fillers are comparable to the values for the reference mortar without filler (REF). The measured expansion level of 0.2–0.3‰ is significantly lower than the requirement set for mortar prisms in the UAMBT test (< 1.0‰).
As the Le Chatelier test and the autoclave test also failed to indicate relevant levels of expansion, we can conclude that the tested MSWI fillers do not cause destructive expansion mechanisms.

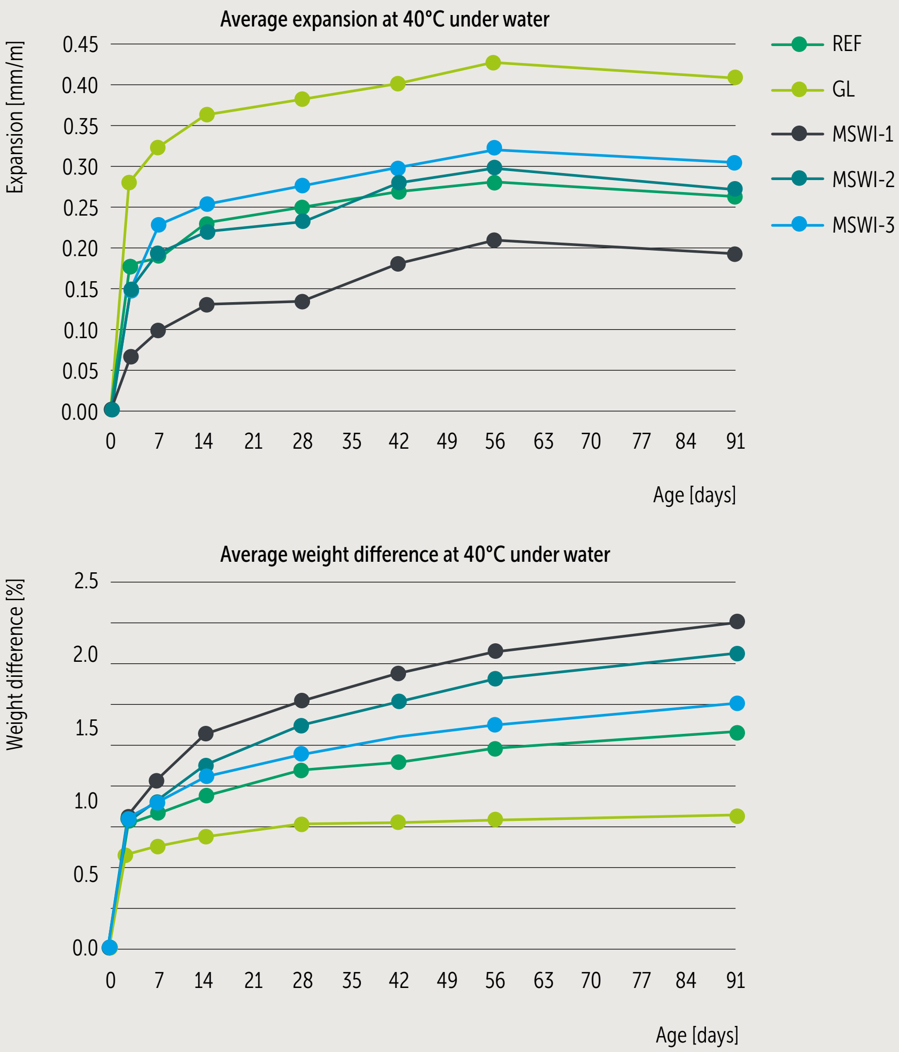


Figure 2. Expansion (top) and weight increase (bottom)

It is interesting to note that the mortar with ground limestone (GL) has a significantly higher level of expansion and less of an increase in weight. This indicates that the ground limestone used has an expansive component. The measured expansion falls within the aforementioned requirements and did not result in cracking.

3.2.4 Mortar tests: Effect of MSWI filler on ASR

The effect of MSWI filler on the alkali-silica reaction (ASR) was studied using the Ultra-Accelerated Mortar Bar Test (UAMBT) in combination with non-reactive and reactive aggregate. The measurements were taken from the slim specimens (25 x 25 x 285 mm) to obtain a higher level of expansion, with the aim of highlighting the effect more clearly. The results obtained are summarized in table 7.

Table 7. Effect of MSWI filler on ASR

Binding agent	Aggregate	Expansion (‰)
100% CEM I 52.5 R	non-reactive	2.2
100% CEM I 52.5 R	reactive	4.2
75% CEM I 52.5 R + 25% MSWI-3	non-reactive	0.4
75% CEM I 52.5 R + 25% MSWI-3	reactive	4.5
75% CEM I 52.5 R + 25% MSWI-1	reactive	3.7
75% CEM I 52.5 R + 25% MSWI-2	reactive	3.7

The reactive aggregate used, borosilicate glass, was found to increase expansion by a factor of approximately 2. However, in combination with the non-reactive aggregate, the MSWI filler did result in significantly lower levels of expansion. There is no obvious explanation for this result. In combination with the reactive aggregate, the MSWI fillers did not have any relevant impact on ASR expansion (roughly the same levels of expansion as the reference mixture). As a result, based on these tests, MSWI filler is not believed to have an inhibiting effect on the ASR.

3.3 Concrete study: 1st life

3.3.1. Composition of concrete tiles

The compositions of the concrete tiles produced at a concrete factory in Drachten are shown in table 8.

Table 8. Compositions (kg/m3)1) of produced concrete tiles

Component	REF	GL	MSWI-1	MSWI-2	MSWI-3
CEM I 52.5 N	289	219	218	219	219
Filler	0	79	73	73	73
Water (effective)	80	89	106	106	105
Absorption water (in aggregate)	11	11	11	11	11
Sand 0–2	791	791	801	794	790
Granite 2–8	1,154	1,154	1,152	1,177	1,157
'Wbf' (effective)	0.28	0.30	0.36	0.36	0.36

1) Excluding approx. 5% V/V air

3.3.2 Mechanical properties

The volumetric weight, the propagation velocity of ultrasonic waves, and the flexural strength were determined for each of the five series of concrete tiles at an age of 28 days. The compressive strength was also measured at an age of 90 days using samples cut from the concrete tiles. The results obtained are summarized in table 9. This table also indicates the effective water-binding factor ('wbf'); although the fillers are type-I fillers, they have been considered part of the 'binding agent' for this purpose.

Table 9. Mechanical properties of concrete tiles

Property	REF	GL	MSWI-1	MSWI-2	MSWI-3
'Wbf' (effective)	0.28	0.30	0.36	0.36	0.36
Volumetric weight (kg/m^3)	2,180	2,210	2,280	2,260	2,270
Ultrasonic velocity (km/s)	3.98	4.07	4.17	4.10	4.06
Calculated dyn. e-modulus (GPa)[1)]	31.0	32.9	35.7	34.2	33.7
Flexural strength (MPa)	5.6	5.6	8.5	7.3	7.6
Volumetric weight (kg/m^3)	2,260	Not calculated	2,280	2,290	2,290
Compressive strength (MPa)	31.7	Not calculated	53.9	51.8	53.6
Flexural/compressive strength ratio (%)	18	Not calculated	16	14	14

1) Calculated with $E_{dyn} = 0.9\rho v^2$ (assuming Poisson's ratio = 0.2)

In spite of the higher 'wbf' (0.36 versus 0.28 for REF and 0.30 for GL), the strength of the concrete tiles with MSWI fillers is significantly higher than that of both references. This can partly be ascribed to better compaction, as is evident from the measured volumetric weight of the concrete tiles; the concrete mixtures with MSWI fillers are more easily compacted. The compressive strength and flexural strength values for the (plastic) mortars with MSWI fillers are significantly lower than those of the reference mortar (see table 6), which can largely be ascribed to the higher air content of the mortars with MSWI fillers. However, in earth-moist concrete – the application for which the CROW-CUR Recommendation is intended – MSWI fillers do not cause an increase in air content; in fact, the opposite is true (see volumetric weights in table 9).

It is also interesting to note that the compressive strength of the reference concrete (REF) is approximately 60% of that of the concrete tiles with MSWI filler; for flexural strength, the value is around 70%. This cannot be explained by the spread of the individual measurement results.

The volumetric weight of the compressive strength specimens in the reference concrete (REF) is 80 kg/m^3 higher than that of the specimens for flexural strength (2,260 versus 2,180 kg/m^3). This is the result of water absorption of approximately 4% (m/m) (see section 3.3.4), which occurs during the 48-hour under-water conditioning prescribed for the compressive strength specimens in NEN-EN 12504-1. During this conditioning process, the specimens with MSWI filler only absorb 0.7% (m/m) (see section 3.3.4), which corresponds to an increase in volumetric weight of approximately 16 kg/m^3. This is in line with the volumetric weights shown in table 9 for concrete tiles with MSWI filler.

3.3.3 Road salt resistance

Road salt resistance was determined at a specimen age of 28 days.
The results obtained are listed in table 10. This table also indicates the water-binding factor for the concrete mixture and the TOC content of the MSWI fillers.

Table 10. Road salt resistance

Property	REF	GL	MSWI-1	MSWI-2	MSWI-3	NEN-EN 1339 requirement
Peeling after 14 cycles (kg/m^2):						
Specimen 1	0.002	0.013	0.009	1.30	1.21	≤1.5
Specimen 2	0.017	0.010	0.042	0.79	1.40	≤1.5
Specimen 3	0.007	0.009	0.053	0.10	1.31	≤1.5
Average	0.01	0.01	0.03	0.73	1.3	≤1.0
'Wbf' (effective)	0.28	0.30	0.36	0.36	0.36	-
TOC filler (%m/m)	-	-	5.8	2.0	0.69	-

The substantially higher wbf of the concrete mixtures with the three MSWI fillers did result in a higher level of peeling in the road salt resistance test. The very small amount of peeling observed with the REF and GL samples can be attributed to their low effective wbf.
In spite of the fact that they all have the same wbf, the three concrete mixtures with MSWI filler all perform very differently when exposed to road salt. The concrete mixture with MSWI-1 filler peels to the same degree as the REF and GL mixtures; the other two mixtures with MSWI filler peeled significantly more. The TOC content of ground limestone is known to affect the road salt resistance of concrete in which it is used; as such, a maximum limit has been imposed for the amount of ground limestone that is permitted in concrete. For the MSWI filler, the TOC content does not seem to have the same impact. In fact, the higher the TOC content, the lower the degree of peeling.

3.3.4 Water absorption and drying

In order to better understand the results obtained in the road salt resistance tests, capillary water absorption and drying tests were also conducted as an addition to the original study program. Concrete tiles that had previously been stored on pallets were placed on laboratory work benches and left to dry out for one month at a temperature of 20˚C and approximately 50% RH. The test specimens were around four months old by the end of this period.
The capillary water absorption was then measured on the tops of the concrete tiles (= formwork surface) for a period of 72 hours. After the absorption test, the weight loss resulting from drying at 20˚C and approximately 50% RV for 144 hours was measured. The results are shown in figure 3.

The degree of water absorption and drying of the concrete tiles with MSWI fillers was significantly lower than that of both reference concrete tiles (REF and GL). The pore structure of the concrete tiles with MSWI fillers is finer (either in spite of, or precisely because of the higher wbf), which results in a less porous concrete.

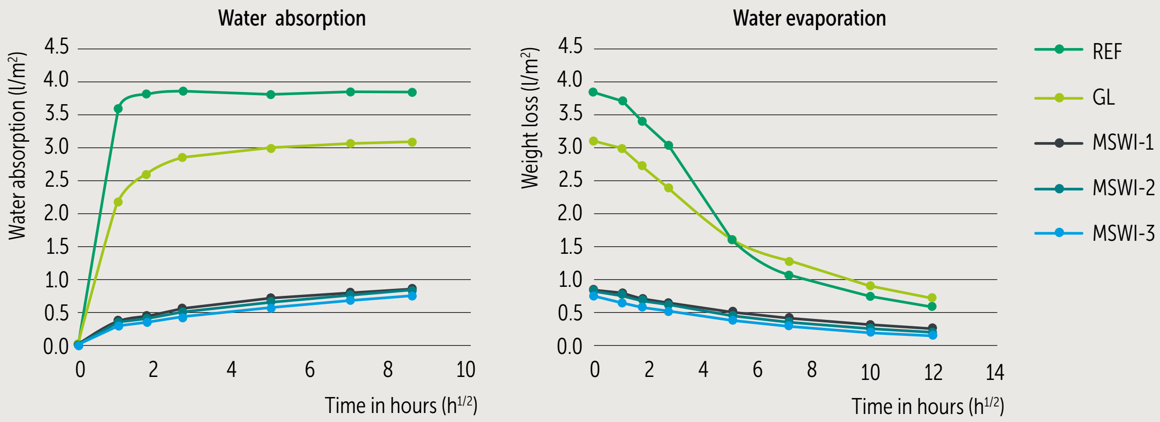


Figure 3. Water absorption (left) and drying (right)

3.3.5 Conclusions of concrete study: 1st life

MSWI fillers can be used as a partial cement replacement to produce earth-moist concrete products with a level of flexural strength and compressive strength that is higher than that achieved by the reference concrete. The road salt resistance of concretes made with MSWI fillers varies a great deal, from very high to the minimum level required by the relevant product standard (NEN-EN 1339). This variation cannot be explained by water absorption and/or the effective water-binding factor of the concrete in question. The higher TOC content of MSWI filler does not have a detrimental effect on the road salt resistance of concrete made with these MSWI fillers.

3.4 Circularity

Based on the results obtained in the study described above, the CROW working group opted to test the MSWI-3 filler, and concrete tiles made using this filler, in this circularity test.

3.4.1 Technological: Concrete granulate

Concrete tiles without filler (REF), with ground limestone (GL), and with the selected MSWI filler (MSWI-3) were broken up in a jaw crusher after two months of rapid hydration at 40˚C.
The concrete was then dry-sieved into particles measuring 4–22 mm.

Characterization of concrete granulate 4–22 mm
The results of the characterization of the three concrete granulates obtained using this method are provided in table 11.

Table 11. Properties of concrete granulates

Property	REF	GL	MSWI-3
Particle distribution (% m/m) (wet sieving)			
22.4 mm	100	100	100
20 mm	98	97	97
16 mm	81	74	77
14 mm	73	69	65
12.5 mm	67	63	57
11.2 mm	61	55	50
10 mm	53	47	44
8 mm	41	34	34
6.3 mm	29	23	23
5.6 mm	25	17	17
5 mm	21	14	13
4 mm	18	11	4
2 mm	8	3	3
1 mm	7	3	2
0.5 mm	6	2	2
0.25 mm	3	1	1
0.125 mm	1	0	1
0.063 mm	0.7	0.3	0.3
Particle density (ρ_{rd}; kg/dm^3)	2.23	2.23	2.23
Water absorption 24 h (% m/m)	6.4	6.4	6.0

The wet-sieving process showed that the REF and GL samples still contained a substantial amount of 2–4 mm particles. The samples used to determine the particle density and water absorption were wet-sieved to remove the particles measuring < 4 mm.
The particle density of the three concrete granulates was the same. The water absorption of the MSWI-3 concrete granulate sample was somewhat lower than that of the REF and GL samples.

Study: 2nd life concrete
Using the aforementioned three samples of concrete granulate as an aggregate, we produced concrete mixtures with the compositions shown in table 12. We determined various properties of these mixtures as listed in the table.

Table 12. Composition and properties of 2nd life concrete

Property	Concrete granulate REF	Concrete granulate GL	Concrete granulate MSWI-3
Concrete composition (kg/m³):			
CEM I 42.5 N	320	320	320
Water, effective	160	160	160
Absorption water	70	70	66
Concrete granulate 4–22 mm	1,049	1,049	1,049
River sand 0–4 mm	666	666	666
Mortar properties			
Slump (mm)	110	120	130
Flow (mm)	400	390	420
Temperature (°C)	19.3	19.0	18.8
Air content (%V/V)	1.8	1.8	1.9
Volumetric weight (kg/m³)	2,235	2,255	2,245
Properties of hardened concrete			
Cube compressive strength (MPa) after:			
7 days	36.5	34.1	36.0
28 days	42.4	42.8	44.0
Volumetric weight (kg/m³) after:			
7 days	2,290	2,290	2,280
28 days	2,290	2,280	2,290
Maximum water ingress (mm)	24	25	13
Chloride migration coefficient ($.10^{-12}$ m²/s)	22.0	21.6	15.7

The results obtained indicate that the concretes made with the three concrete granulates are comparable in terms of compressive strength. The value is also comparable to that of the reference concrete (with the same effective wcf and cement) tested after 28 days of hardening in the CROW project 'New recycling methods for aggregates' (46.5 MPa).
The density (resistance to the ingress of water and chloride ions) of the concrete with the MSWI-3 concrete granulate is better than that achieved by the REF and GL granulates. These results also correspond to those obtained in the aforementioned CROW project.

In spite of the limited scope of this study, we can justifiably conclude that the technological quality of concrete granulate made with MSWI fillers is comparable to that of standard concrete granulate and therefore that the use of this filler does not limit the 2nd life application of this concrete.

3.4.2 Technological: Filler

We produced cement pastes with 100% CEM I 52.5N (REF), 75% CEM I 52.5N + 25% ground lime-stone (GL), and 75% CEM I 52.5N + 25% MSWI filler MSWI-3. The wbf of the three pastes produced was 0.35. These three cement pastes were rapidly hydrated for two months under water at a

temperature of 40°C. The hardened specimens were broken up in a laboratory jaw crusher, dried out at 110°C, and then milled for 20 minutes in a ball mill. The particle distribution of these three '2nd life' fillers is shown in table 13.
The table also shows the effect of these fillers on the setting time, soundness, and strength of the cement at 25% (m/m) cement replacement (CEM I 52.5N).

Table 13. Properties of 2nd life fillers

Property	Cement	REF	GL	MSWI-3	BRL 1804 requirement
Particle distribution, sieved residues (% m/m):					
0.5 mm	-	0	1	0	-
0.25 mm	-	1	2	1	-
0.125 mm	-	4	6	3	0-15
0.063 mm	-	23	27	22	0-30
Fraction <63 µm	-	77	73	78	-
	100% cement	at 25% (m/m) cement replacement			
Water requirement (% m/m)	24.2	28.6	29.0	29.0	-
Start of setting (min)	140	190	195	220	-
Difference in value compared to cement	-	+50	+55	+80	<120
End of setting (min)	170	240	235	260	-
Difference in value compared to cement	-	+70	+65	+90	<120
Soundness (mm)	0.0	0.5 0.5		0.0	<10
Compressive strength (MPa) after:					
7 days	39.8	35.0	32.3	31.9	-
28 days	47.7 (100%)	41.7 (87%)	38.5 (81%)	40.6 (85%)	> 65%
Flexural strength (MPa) after:					
7 days	6.8	6.3	5.8	5.5	-
28 days	7.5 (100%)	6.8 (91%)	6.7 (89%)	6.5 (87%)	-
Volumetric weight (kg/m^3) after:					
7 days	2,260	2,200	2,200	2,210	-
28 days	2,238	2,201	2,181	2,200	-

Table 13 shows that all three of the tested '2nd life' fillers slowed down the setting process.
This is inherent with 25% m/m replacement of cement and the associated higher wcf. The MSWI-3 '2nd life' filler results in a somewhat longer setting time than both reference fillers, but the value is still within the required range.
Soundness (Le Chatelier test) was excellent for all three of the tested '2nd life' fillers. The same is true of their impact on compressive strength, which is also well within the required range.

Based on these results, we can conclude that there are no limitations on the reuse of the powder fraction generated when recycling 1st life concrete manufactured with MSWI fillers.

3.4.3 Environmental

After 28 days of hardening at 20°C (packed in plastic film = own moisture content; no contact with water), a number of the concrete tiles without filler (REF) and with MSWI-3 filler were broken down into granulate measuring < 4 mm. Both of these broken-up samples were tested for leaching using a column test. The results obtained are summarized in table 14, which also indicates the requirements from the Dutch Soil Quality Decree (BBK) for non-molded building materials.

Table 14. Leaching (column test) of broken concrete tiles, REF and MSWI-3

Component	**Cumulative leaching L/S 10 (mg/kg)**		
	Concrete granulate REF	**Concrete granulate MSWI-3**	**Max. value in BBK**
pH	12.5–12.8	12.5–12.8	-
Antimony	<0.0040	0.0060	0.32
Arsenic	<0.050	<0.050	0.9
Barium	6.4	11	22
Cadmium	<0.00100	<0.00100	0.04
Chromium	0.16	0.27	0.63
Cobalt	<0.030	<0.030	0.54
Copper	0.071	0.13	0.9
Mercury	<0.00040	<0.00040	0.02
Lead	<0.100	<0.100	2.3
Molybdenum	0.037	0.071	1
Nickel	<0.050	<0.050	0.44
Selenium	<0.0070	<0.0070	0.15
Tin	<0.020	<0.020	0.4
Vanadium	<0.20	<0.20	1.8
Zinc	<0.20	<0.20	4.5
Fluoride	2.6	2.3	55
Chloride	61	110	616
Sulfate	60	52	2,430
Bromide	<0.80	<0.80	20

This table shows that concrete granulate with MSWI-3 leaches the components barium, chromium, copper, molybdenum, and chloride to a greater degree than concrete granulate without filler (REF). In all cases, the amount of leaching is still well within the BBK requirements.

We can conclude that the environmental quality of concrete granulate with MSWI fillers is comparable to that of standard concrete granulate. The slightly elevated levels of leaching of some components are still well within the requirements of the BBK.

4 Conclusions: Suitability of MSWI filler

Based on the studies conducted, we can conclude that the MSWI filler produced by Blue Phoenix Group is suitable for use in unreinforced, non-construction concrete products made with dry or earth-moist concrete mortar.
The study also showed that, when MSWI filler is used in these products, the material streams generated when the concrete in question is recycled (concrete granulate and powder fraction) can be reused as a raw material in a 2nd life concrete. This application of MSWI filler is therefore fully circular in terms of the aspects within the scope of this study.

5 CROW-CUR Recommendation

BRL 1804 includes generic requirements that apply to all fillers, including MSWI fillers.
These requirements relate to:
- Particle distribution
- Methylene blue adsorption
- Alkali content, expressed as Na_2O equivalent
- Chloride content
- Sulfate content – SO_3
- Effect on setting time
- Determination of soundness
- Effect on strength

Based on the tests carried out, the following aspects of MSWI filler require further specific consideration:
- Alkali content:
  This value is usually determined using XRF, which provides a total content including alkalis in glass particles. The alkalis in glass particles are only released if the amorphous glass dissolves in the alkaline environment of the concrete. However, the glass will never fully dissolve.
  If the XRF measurement result for the alkali content exceeds the set limit value of 5.0% (m/m),

this does not immediately result in rejection; the alkali content of the MSWI filler may be recalculated with alkali digestion in accordance with NEN-EN 196-2 and then checked against the requirement.

- TOC content:
  The TOC content of the MSWI filler does not appear to have a negative impact on the road salt resistance of the concrete. However, a higher TOC content can result in a longer cement setting time. Based on the results obtained in the conducted tests, the TOC content of the MSWI filler should therefore be limited to a maximum of 6% (m/m).
  As the impact on setting time is a generic requirement, an additional safeguard is in place for this aspect.
- Metallic Al+Zn:
  In an alkaline environment, metallic aluminum and zinc can cause hydrogen gas to form. These metals may be present in small amounts in MSWI bottom ash, the raw material for the production of MSWI filler. Due to the production process (wet milling and an alkaline environment) and the fineness of the MSWI filler, the metallic Al + Zn content will be very low. For this reason, a strict requirement of a maximum of 0.2% (m/m) has been prescribed for MSWI filler.
  This requirement is five times lower than the requirement for MSWI granulate, which is dosed at four times the level of MSWI filler in concrete. This requirement is therefore 20 times stricter than the requirement for MSWI granulate, which has been in widespread use in concrete paving slabs and tiles for many years without any issues.

Although there are no requirements for the chloride content of fillers in BRL 1804, because the requirements apply to the concrete mortar in accordance with NEN 8005, a decision has been made to include a requirement in the CROW-CUR Recommendation as an extra safeguard for MSWI filler. A chloride level of $\leq$ 1.0% (m/m) at a MSWI filler dose of maximum 80 kg/m^3 of concrete (equivalent to approximately 25% (m/m) in cement), the chloride content of the resulting concrete granulate will be $\leq$ 0.05% (m/m). This value corresponds to the 'Guidelines for specifications for recycling granulates for concrete' published by Betonhuis/BRBS.
N.B.: At higher doses of MSWI filler in concrete, the chloride content requirement is reduced accordingly. At the maximum permitted dose of 140 kg/m^3, the requirement for chloride content is: < 0.6% (m/m).

It may be a good idea to consider placing a note in the CROW-CUR Recommendation stating that the use of MSWI filler in unreinforced concrete products made with earth-moist concrete can lead to increased sensitivity to peeling when exposed to road salt. However, as these kinds of concrete products are almost always used with a top layer that does not contain MSWI filler, this is not relevant.

6 Afterword

This afterword explores a number of aspects that are not directly related to the tests performed and the objective of this report, but that are important to developing a sound understanding of the use of MSWI filler in concrete.

The difference between MSWI granulate and MSWI filler is not always clear. These materials have different functions in concrete (they are used as an aggregate and as filler respectively) and they have very different effects on the properties of the concrete in which they are used.

Due to the consumption of $Ca(OH)_2$, CROW-CUR Recommendation 128: 2021 limits the use of MSWI filler to 140 kg/m^3 of concrete. In the long term, excessive consumption of $Ca(OH)_2$ results in carbonation, which affects the CSH gel and creates a porous silica gel. This significantly reduces the ability of the concrete to withstand freezing and thawing cycles.

If the MSWI filler meets the chloride content requirement described in chapter 5, there is no risk of chloride-initiated reinforcement corrosion when using concrete granulate that contains MSWI filler in 2^{nd} life concrete.

The same is true of the road salt resistance of concrete granulates that contain MSWI filler.
The degree of peeling measured in the concrete tiles with MSWI filler is comparable to or even less than the level observed in standard concrete, which is used to produce traditional concrete granulates.

The tests carried out, in conjunction with the considerations above, demonstrate that concrete granulates that contain MSWI filler are of comparable quality to traditional concrete granulate and are suitable for use as aggregate in concrete (2^{nd} life). The same regulations can be applied to these concrete granulates.

As MSWI filler makes a significant contribution to the strength of the concrete due to its pozzolan properties, this filler will consume a substantial amount of $Ca(OH)_2$ in the concrete. For this reason, the MSWI filler must be taken into account when calculating the minimum Portland cement clinker content in the binding agent. We recommend calculating the limestone-binding capacity of the MSWI filler.

Appendix A Origins and representativity of input material samples

CROW working group:
"MSWI filler as a type 1 filler for use in unreinforced concrete"
Origins and representativity of input material samples

Date: 3/3/2021

Introduction
For the purposes of the study program for the CROW-CUR Recommendation *'MSWI Filler in Unreinforced Earth-Moist Concrete'*, Blue Phoenix Group BPG supplied three samples of MSWI filler to SGS Intron. This memo provides further information on the raw materials used (= MSWI bottom ash), the milling process, and the representativity of the raw materials and the filler produced.

Origins of input material for production of samples of MSWI filler
On the request of the working group, we opted to supply samples that are representative of MSWI bottom ash in the Netherlands. The working group also requested MSWI bottom ash with varying levels of sulfate and TOC, in order to evaluate the effects of sulfate/TOC when used in concrete. BPG used bottom ash sourced from three of the twelve MSWIs in the Netherlands: AVR Duiven, AVR Rozenburg and EEW Delfzijl. Material sourced from AVR Duiven had high values for sulfate and TOC.

The 12 Dutch MSWIs produce a total of approximately 1,900,000 T of MSWI bottom ash. The three sites used for sampling produce around 600,000 T of MSWI bottom ash. They are responsible for around 30% of the total volume and the plants are geographically distributed across the Netherlands.

MSWIs & MSWI bottom ash:
- Process description (Board of Experts, Raw Materials & Environment, 02-21-2018)
  - MSWI bottom ash is created when domestic waste and commercial waste materials (including biomass) are combusted in a municipal solid waste incinerator (MSWI) or biomass energy plant.
    Combustion takes place in a grate incinerator or fluidized bed incinerator at a minimum combustion chamber temperature of 850°C. Once the combustion process is complete, the remaining bottom ash is extinguished in a water basin and then conveyed to an interim storage point before further processing takes place. During processing, the raw bottom ash undergoes a number of processing steps, including sieving and the removal of ferrous and non-ferrous metals. MSWI boiler ash may form part of the MSWI bottom ash; at most plants, the two are combined in the plant. Bottom ash from a biomass energy plant may also form part of the MSWI bottom ash; this bottom ash is added in doses during processing.
- The MSWI bottom ash is then broken up into particles with a D_{max} of 40 mm; this fraction is the input material for the MSWI filler production process.
- The MSWIs satisfy the IPPC guidelines (see appendix 1)
- MSWIs have a strict policy in relation to materials coming into the plant, and they regularly check the waste delivered to the plant. The types of waste that can be delivered to the plant are contractually defined (between the customer and the MSWI responsible for combustion); random checks are carried out regularly, and waste loads are deposited on the floor for visual inspection.

- RIVM takes samples annually to determine the average composition of waste produced in the Netherlands.
- The MSWI bottom ash meets the requirements set out in BRL 2307-1. The requirements may be met through batch surveys or a process certificate.
- MSWI fly ash is kept separate and is therefore not present in the MSWI bottom ash.

BEP ash

Biomass energy plant (BEP) bottom ash: Of the 12 MSWIs in the Netherlands, only AVR Rozenburg, HVC Alkmaar, and Twence produce BEP bottom ash. BEP bottom ash from AVR Rozenburg and HVC Alkmaar is added to the MSWI bottom ash. HVC only adds the coarse fraction to MSWI bottom ash. In total, AVR Rozenburg and HVC Alkmaar add approximately 7,000 T of BEP bottom ash to approximately 600,000 T of MSWI bottom ash. No BEP bottom ash is added to the other 1,300,000 T of MSWI granulates. Further information on
BEP ash is provided in appendix 2.

Sampling the supplied samples

The samples were taken by the laboratory technician from Blue Phoenix; at AVR, this was done in conjunction with the relevant member of staff at AVR.
The same approach was taken in each location:
- Raw bottom ash was taken from:
  - AVR Duiven: from the raw bottom ash pile directly behind the wet slag remover.
  - AVR Rozenburg: from the raw bottom ash store.
  - EEW: from the raw bottom ash store in Wijster.
- Using a crane and a truck, a volume of approximately 30–50 T was set aside.
- This 30–50 T of raw MSWI bottom ash was then evenly spread out using the crane.
- Samples were then taken from this spread-out layer using a crane.
- The samples were taken from evenly distributed points across the raw bottom ash.
- The crane was used to place the samples in around 5–10 big bags with a capacity of approximately 1 m^3.

All of the big bags were transported to the Blue Phoenix processing plant in Rotterdam/Pernis, where they were processed in the MSWI filler plant.

Representativity of the samples taken

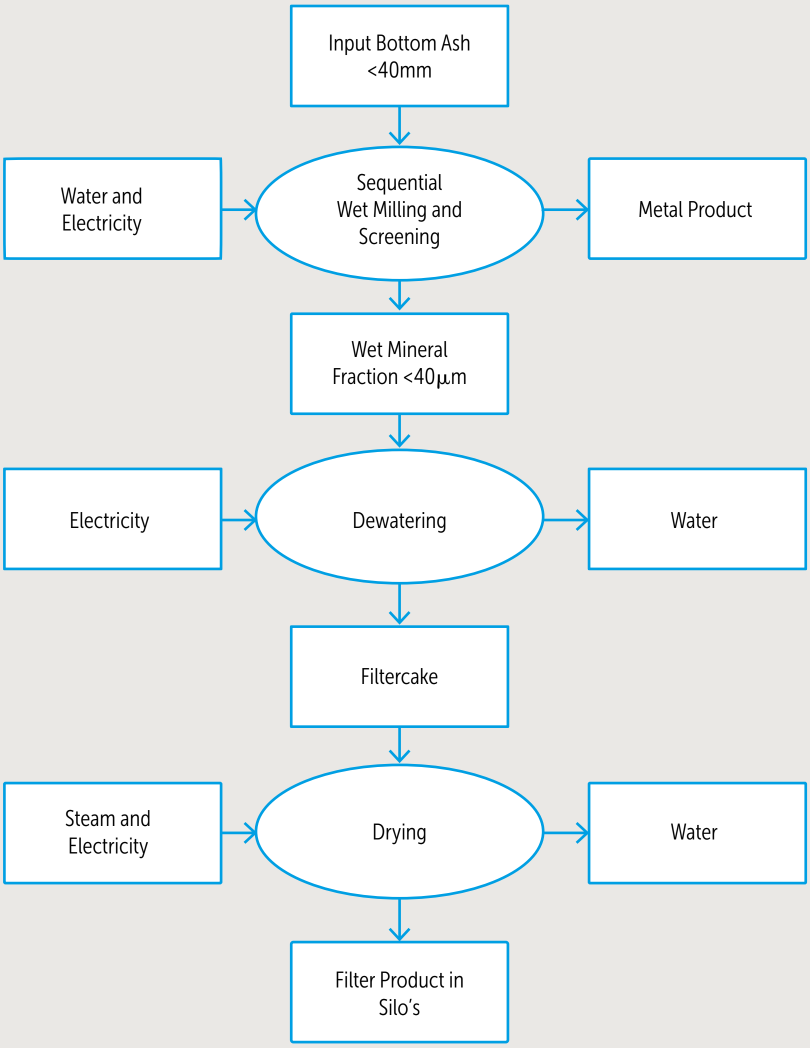
The MSWI filler produced from these samples was subjected to a chemical analysis. The concentration of the main elements can be used to assess the representativity of the samples taken from the MSWIs by comparing them with earlier analyses and data from the literature.

The representative analyses/reports below had already been sent to the CROW working group:
1. Elementary analysis of two Dutch bottom ash samples and one British bottom ash sample (SGS 05-15-2020)
2. Characterization of one MSWI source in the Netherlands from three different periods (SGS 11-13-2018)
3. Characterization of three MSWI sources geographically distributed across the Netherlands (SGS 12-03-2020)

All of the measurements are summarized in the table below. The results provide a representative picture of the quality of the bottom ash. The figures are geographically spread across the Netherlands and are a representative portion of the total volume; they also reflect developments over a specific period of time at a single location. All of the XRF measurements were performed in the same way.

Table 1. Chemical analysis of waste combustion plant bottom ash in samples supplied to CROW (% wt)

SGS report	MSWI filler EEW 11-13-2018			MSWI filler DVN 12/3/2020	MSWI filler RZB 12/3/2020	MSWI filler EEW 12/3/2020	MSWI filler UK 5/15/2020
	Sept. 2018	Oct. 2018	Nov. 2018				
Silicon as SiO_2	49.61	50.25	46.22	50.07	47.61	50.46	43.92
Calcium as CaO	18.08	16.38	18.44	18.18	17.03	16.41	20.74
Iron as Fe_2O_3	11.67	11.18	12.33	7.90	11.04	10.59	11.30
Aluminum as Al_2O_3	7.54	8.26	8.53	7.43	8.23	7.98	8.93
Sodium as Na_2O	3.73	4.33	3.84	4.13	4.13	3.94	3.91
Sulfur as SO_3	2.27	1.84	2.62	2.69	1.60	1.64	2.02
Magnesium as MgO	2.00	1.96	2.05	2.39	2.42	2.02	2.02
Phosphorus as P_2O_5	1.08	1.01	1.18	1.10	1.23	0.94	1.06
Titanium as TiO_2	1.24	1.07	1.29	1.15	1.32	0.98	1.26
Potassium as K_2O	0.92	0.86	0.99	1.01	0.97	1.02	0.81
Zinc as ZnO	0.55	0.58	0.69	0.54	0.60	0.50	0.69
Chloride as Cl	0.77	0.59	0.72	–	–	–	–
Copper as CuO	0.28	0.31	0.35	0.31	0.38	0.27	0.31
Manganese as MnO	0.16	0.23	0.19	–	–	–	0.29
Manganese as Mn_3O_4				0.16	0.21	0.18	–
Lead as PbO	0.12	0.13	0.14	0.11	0.11	0.11	0.12
Chromium as Cr_2O_3	0.08	0.11	0.09	0.10	0.11	0.09	0.10
Zirconium as ZrO_2	0.04	0.05	0.03	0.14	0.06	0.07	0.05
Barium as BaO	0.11	0.10	0.14	0.21	0.27	0.20	0.18
Strontium as SrO	0.07	0.07	0.08	0.07	0.05	0.05	0.04
Iodine as I				–	–	–	–
Nickel as NiO				0.02	0.03	0.03	0.03
Vanadium as V_2O_5				0.01	0.01	0.01	–



MSWI filler production process

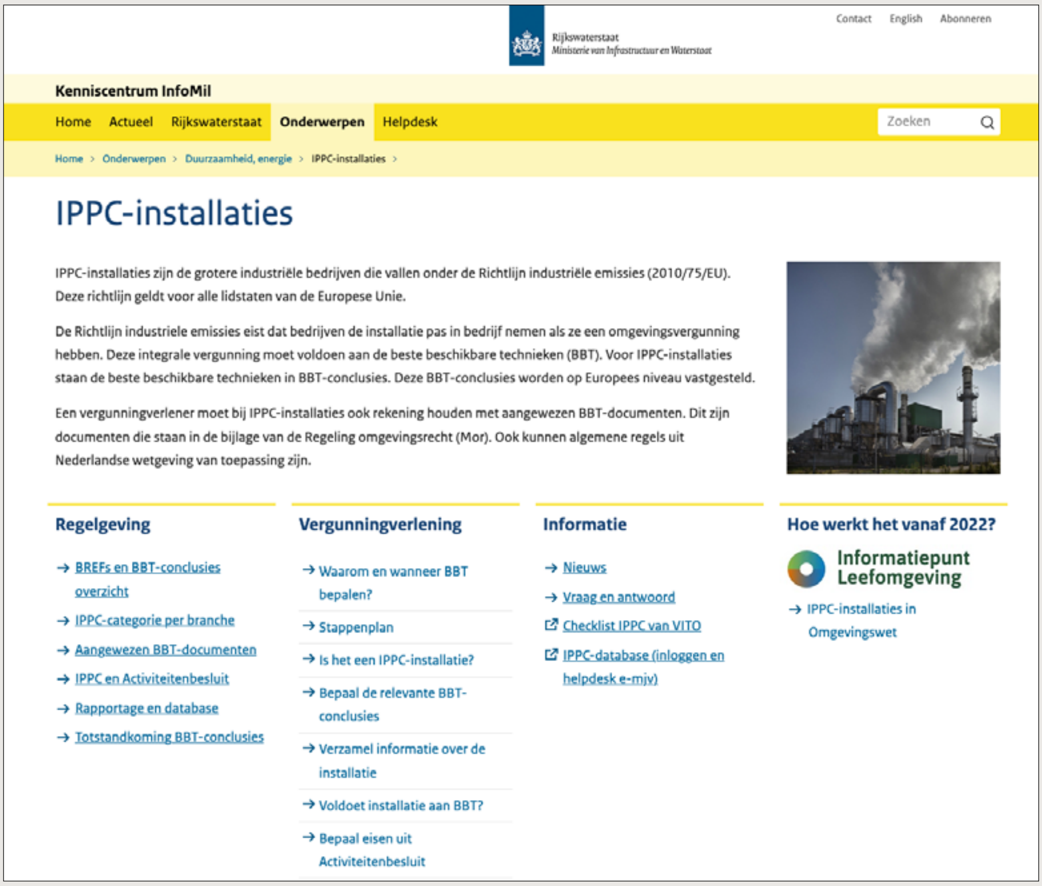
The raw materials received were milled using the BPG pilot plant in Rotterdam. A wet milling process was used. The aim of the process was to achieve a sufficiently fine result and to remove disruptive materials such as metallic aluminum. Chloride, sulfate, and organic materials (TOC) were not removed during processing. This trial production process for research purposes aimed to maintain the high levels present.

Conclusion

The MSWI bottom ash is comprised primarily of silicates and calcium oxides, supplemented with iron and aluminum oxides respectively.
BEP ash is added in very small amounts. The AVR Rozenburg sample contained the highest amount of BEP ash; AVR is part of the overall R&D program. The BEP ash analyses are provided in appendix 2.

Appendix 1: IPPC installation

https://www.infomil.nl/onderwerpen/duurzaamheid-energie/ippc-installaties/



Appendix 2: BEP ash

The 'Residual materials' working group at the Dutch Waste Management Association (DWMA) discussed the CROW working group's request for information on 'BEP ash'. The matter was then discussed with the three producers of BEP ash in the Netherlands. The information below was compiled following consultation between the three DWMA members who produce both MSWI bottom ash and BEP ash.

The DWMA reported on the tonnages for 2019 (rounded figures):

- MSWI bottom ash in the Netherlands: 1,900,000 T
- MSWI bottom ash in each location where BEP ash is also produced
  - AVR Rozenburg 350,000 T
  - HVC 240,000 T
  - Twence 150,000 T
- Biomass energy plant ash 15,700 T
  - AVR Rozenburg 5,500 T
  - HVC 1,250 T
  - Twence 9,000 T
- BEP ash from Twence is not mixed with MSWI bottom ash;
- Summary: 7,000 T/Y (1.2%) mixed with MSWI bottom ash.

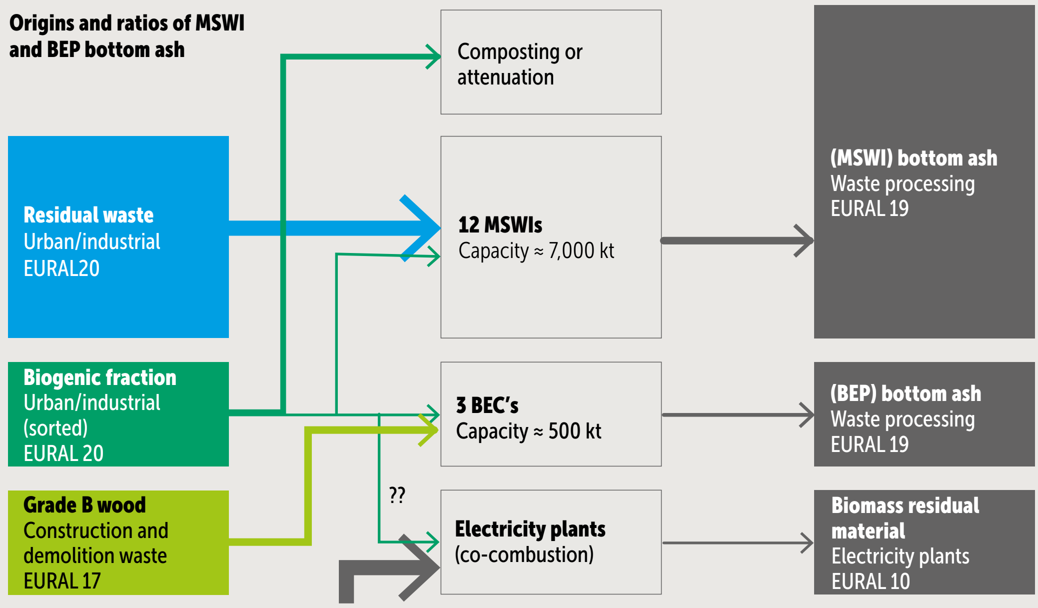


Diagram of BEP ash

Chemical analyses of BEP ash (AVR RZB)

Results		
Analysis	**Unit**	
XRF elementary composition		**WROXI**
SiO_2	% (m/m) d.w.	48.26
CaO	% (m/m) d.w.	20.53
Fe_2O_3	% (m/m) d.w.	5.07
AL_2O_3	% (m/m) d.w.	7.26
Na_2O	% (m/m) d.w.	1.85
SO_3	% (m/m) d.w.	2.40
MgO	% (m/m) d.w.	2.39
P_2O_5	% (m/m) d.w.	0.69
TiO_2	% (m/m) d.w.	6.58
K_2O	% (m/m) d.w.	1.48
ZnO	% (m/m) d.w.	0.54
Cl	% (m/m) d.w.	–
CuO	% (m/m) d.w.	0.20
Mn_3O_4	% (m/m) d.w.	0.24
Pbo	% (m/m) d.w.	0.19
Cr_2O_3	% (m/m) d.w.	0.11
ZrO_2	% (m/m) d.w.	0.04
BaO	% (m/m) d.w.	0.86
SrO	% (m/m) d.w.	0.08
NiO	% (m/m) d.w.	0.02

Appendix B Details of XRD and XRF measuring methods

XRD

Quantitative X-ray diffraction patterns (XRD) were used to determine the mineralogical composition of the three MSWI fillers.

The calculation was performed using a Bruker D8 Advance diffractometer with Bragg-Brentano geometry and a Lynxeye position-sensitive detector. 45 kV 40 mA Cu Kα radiation and a V12 divergence split with a height of 5 mm were used. Detection setting: LL 0.19 and W 0.06.

The 2θ scan was performed between 10–110° with a step size of 0.030° and a measurement time of two seconds per step.

The data obtained was processed using the Bruker software Diffrac.EVA, version 4.3.

XRF

X-ray fluorescence spectroscopy was used to determine the element composition of the three MSWI fillers.

The calculation was performed using an Axios WD-XRF Panalytical with a 2.4 kW X-ray tube.

AP WROXI was used as the analysis method, with a Panalytical package of 21 oxides made from synthetic standards. The standards were used to make glass beads by mixing a quantity of the standard with LiT:LiM (ratio 66%:34%) and then melting it.

A list of the wavelengths used for each element is available.

Appendix C Production of concrete tiles

On Friday 09-11-2020, a concrete factory in Drachten produced concrete paving tiles measuring 300 x 300 x 60 mm using the five concrete mixtures under investigation. For each mixture, a batch of 1.25 m^3 of concrete was produced; this was then used to produce just over 200 tiles on a small tile press. The tiles produced did not have a top layer.

The composition of the five concrete mixtures is described in the table below.

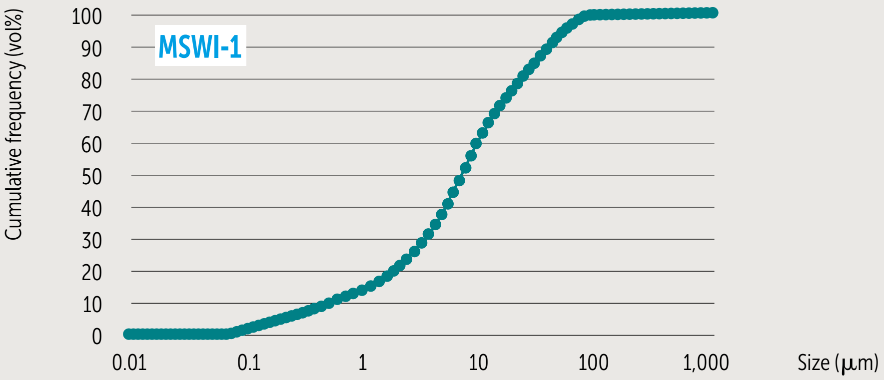
Compositions (kg/m^3) of concrete paving tiles

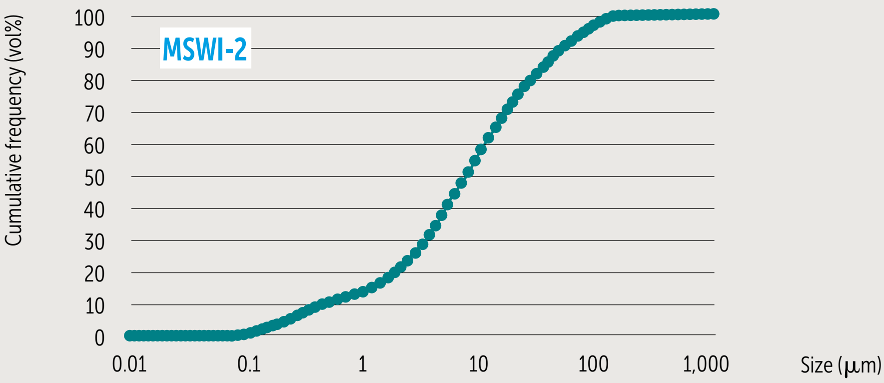
Component	REF	GL	MSWI-1	MSWI-2	MSWI-3
CEM I 52.5 N	289	219	218	219	219
Filler	0	79	73	73	73
Water (effective)	80	89	106	106	105
Absorption water	11	11	11	11	11
Sand 0–2	791	791	801	794	790
Granite 2–8	1,154	1,154	1,152	1,177	1,157
Wbf (effective)	0.28	0.30	0.36	0.36	0.36

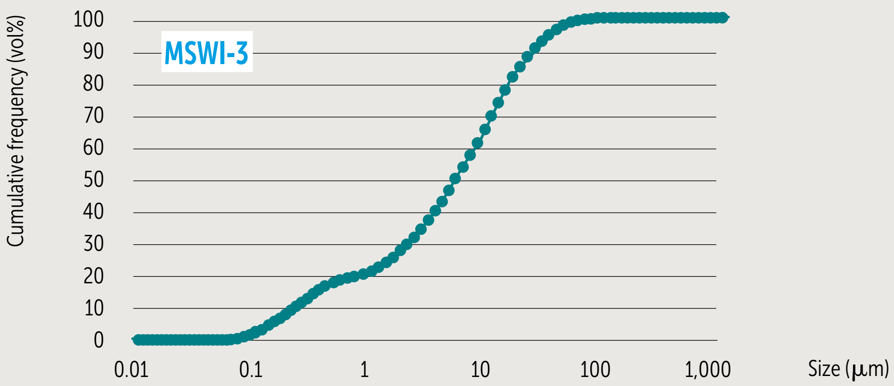
The reference mixture (REF) was the basic formula for these concrete tiles. To achieve a uniform consistency (consistency was assessed by the mill foreman, by kneading the mixture into a ball and judging the consistency), the water content of the concrete mixture with ground limestone was increased by 9 l/m^3.
Although this consistency produced good results with both concrete mixtures, the employees operating the tile press indicated that both mixtures were 'on the dry side' and the consistency of the three concrete mixtures with MSWI fillers was adjusted slightly. This adjustment, in combination with the slightly higher water requirement of the three MSWI fillers, resulted in these mixtures requiring approximately 17 l/m^3 additional water in the mixture compared to the mixture with ground limestone.

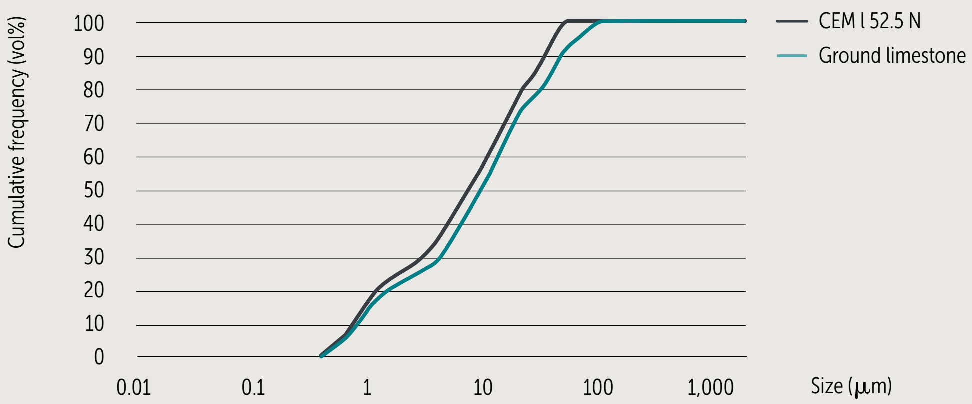
Some of the concrete tiles produced were delivered to the SGS INTRON laboratory in Sittard on 09-22-2020. Each concrete mixture was packed on a separate pallet.

Appendix D Particle distributions in fillers and cement









Appendix E X-ray diffraction patterns

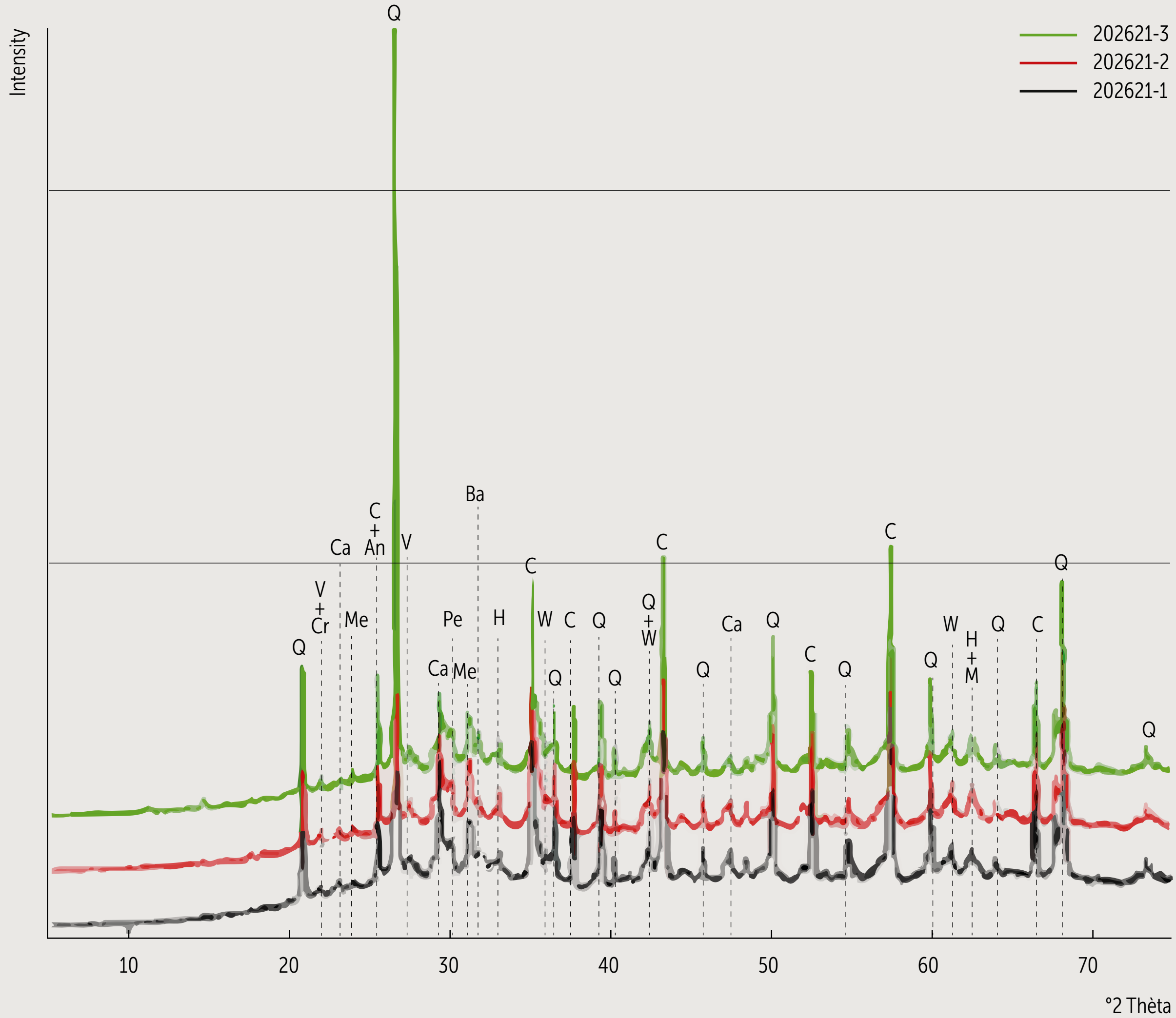
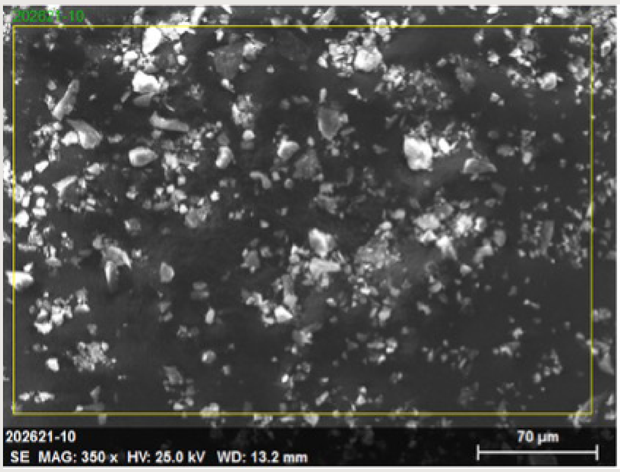


Figure 1. Diffraction patterns of the samples. The key reflections have been labeled: internal standard (C), quartz (Q), feldspar (V: both plagioclase/albite and alkali feldspar), cristobalite (Cr), melilite-type minerals (Me), petedunnite (Pe), bassanite (Ba), calcite (Ca), hematite (H), magnetite (M) and wüstite (W), anhydrite (An).

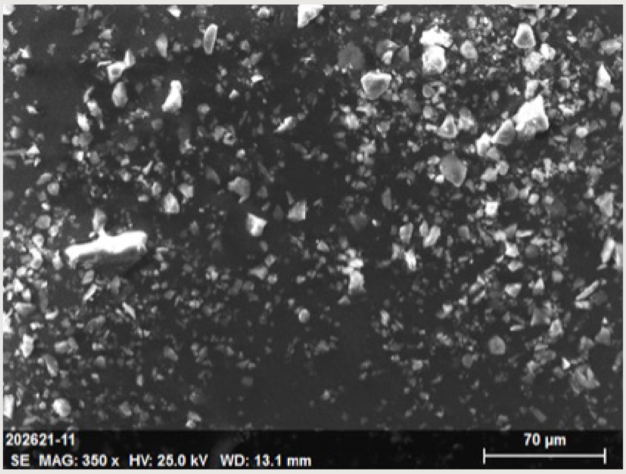
Appendix F SEM/EDAX

MSWI-1 filler



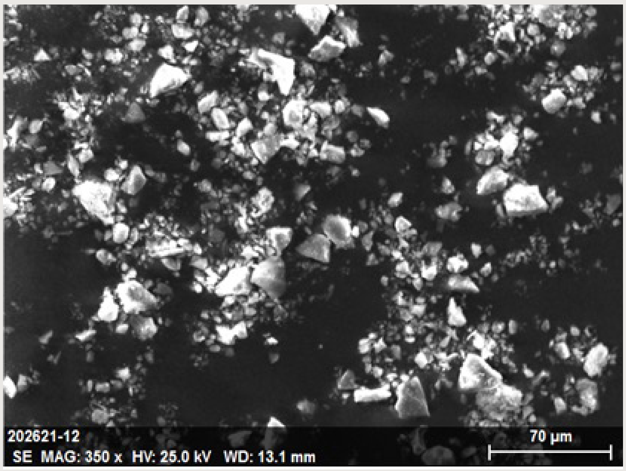
E1	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Na	11	K-series	0.90	6.79	9.52	0.10
Mg	12	K-series	0.25	1.91	2.53	0.05
Al	13	K-series	0.90	6.79	8.11	0.08
Si	14	K-series	4.31	32.46	37.25	0.22
P	15	K-series	0.43	3.22	3.35	0.05
S	16	K-series	1.32	9.91	9.97	0.08
Cl	17	K-series	0.20	1.48	1.35	0.04
K	19	K-series	0.21	1.56	1.28	0.04
Ca	20	K-series	3.47	26.12	21.01	0.14
Fe	26	K-series	1.30	9.76	5.63	0.08
Total			**13.28**	**100.00**	**100.00**	

MSWI-2 filler



E1	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Na	11	K-series	1.20	6.91	9.73	0.12
Mg	12	K-series	0.50	2.86	3.81	0.06
Al	13	K-series	1.52	8.69	10.42	0.11
Si	14	K-series	5.43	31.18	35.92	0.27
P	15	K-series	0.58	3.31	3.46	0.05
S	16	K-series	1.27	7.27	7.33	0.08
Cl	17	K-series	0.26	1.48	1.35	0.04
K	19	K-series	0.17	0.97	0.80	0.03
Ca	20	K-series	4.25	24.39	19.69	0.16
Fe	26	K-series	2.25	12.93	7.49	0.09
Totaal			**17.43**	**100.00**	**100.00**	

MSWI-3 filler



E1	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Na	11	K-series	1.55	6.60	9.42	0.14
Mg	12	K-series	0.38	1.61	2.17	0.05
Al	13	K-series	2.14	9.14	11.12	0.14
Si	14	K-series	7.54	32.20	37.62	0.36
P	15	K-series	0.49	2.11	2.23	0.05
S	16	K-series	1.29	5.51	5.63	0.08
Cl	17	K-series	0.32	1.37	1.27	0.04
K	19	K-series	0.23	0.97	0.82	0.04
Ca	20	K-series	6.00	25.63	20.99	0.21
Fe	26	K-series	3.48	14.86	8.73	0.13
Total			**23.42**	**100.00**	**100.00**	

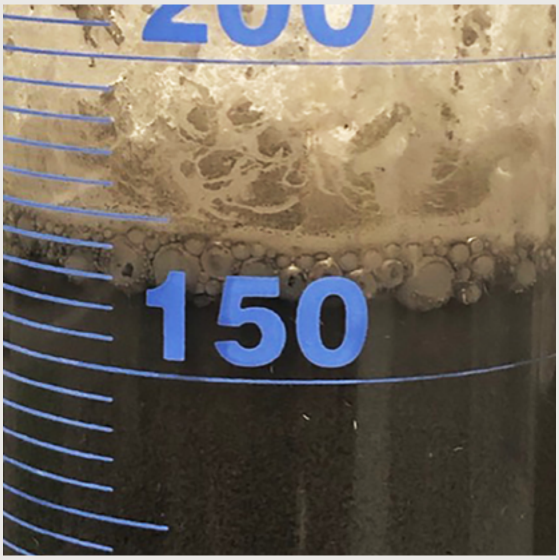
Appendix G MSWI filler foam test

Method:
Add 15 g of MSWI filler + 150 ml demineralized water to a 500 ml measuring cylinder. Stir using a glass rod and measure the amount of foam created.
Use a thin hose to blow compressed air into the bottom of the measuring cylinder for 30 seconds. Measure the amount of foam once the larger, less stable air bubbles have disappeared.

Results:

Filler	MSWI-1	MSWI-2	MSWI-3
Amount of foam after mixing with water (ml foam/gram filler)	1.3	1.3	0.3
Amount of foam (stable) after blowing air in (ml foam/gram filler)	1.7	0.7	0.7
Air content of mortar (%V/V)	10.0	11.5	6.8
N.B.: Measurement accuracy approximately 0.3 ml/g			

Interpretation:
All three of the fillers create foam when gently mixed (stirred); when air is introduced, the amount of foam increases (somewhat) in MSWI-1 and MSWI-3. In MSWI-2, the amount of foam decreases. It is interesting to note that significantly less foam formed on the sample MSWI-3 when stirred, compared to MSWI-1 and MSWI-2, which corresponds to the significantly lower air content of the mortar containing MSWI-3 (bottom row of the table).
It would therefore appear that there are foaming (= surface-tension-active) components present. A substantial proportion of the air bubbles formed are smaller than 1 mm and are difficult to remove from the mortar using vibration/shocks.



Colofon

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Blue Phoenix Group

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