Environmental interactions of cement-based products

Citation for published version (APA):

Document status and date:
Published: 01/01/2016

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 13. Jul. 2020
Environmental Interactions of Cement-Based Products

M.V.A. Florea

Eindhoven University of Technology, the Netherlands

Abstract
The environmental interactions of concrete and other cement-based products encompasses both the influence of such materials on their environment, as well as the effects of the environment on the materials in time. There are a number of ways in which the environmental impact of concrete can be reduced. Employing sustainable energy sources such as municipal solid waste or waste wood or paper, increasing the durability of concrete structures by increasing its resistance to chloride attack, upgrading recycled concrete as building material and incorporating industrial by-product in concrete mixes are just a few examples. All these methods come together in more ways than one: the incineration of municipal wastes or biomass will generate materials which can be used as additions in concrete; the intelligent processing of construction and demolition waste will generate new materials for the production of clinker as well as recycled aggregates that can replace the natural gravel in concrete and the use of industrial by-products can contribute to the durability of concrete—both from the mechanical properties point of view, as well as from the perspective of resistance to aggressive environments.

Keywords: environmental impact, incineration, by-products, recycling

Corresponding author's email: M.V.A.Florea@tue.nl
Introduction
The most produced material worldwide is concrete - twice as much is used in construction around the world than the total of all other produced materials, including wood, steel, plastic and aluminium. The annual global production of concrete is about 3.8 billion cubic meters [1]. The main constituents of concrete are cement, aggregates (sand and gravel) and water. Ordinary Portland Cement (OPC) and natural aggregates (limestone, quartz etc.) are considered primary materials for concrete mixes. Streams of secondary materials can be used to replace primary materials; these include supplementary cementitious materials for the replacement of cement (ground granulated blast furnace slag and coal combustion fly ash being the most common ones) or of the aggregates (recycled concrete particles, mining waste streams etc.). The manufacture of concrete requires ~ 0.7 GJ/ton of energy, when only the cement production, aggregate use and plant operation are taken into consideration [2]. Transport costs, for instance, will further increase this value. Around 8-12% of the concrete composition is cement, with an global production of 3.6 billion t in 2011 [3]. Producing one ton of cement requires about 2 tons of raw materials (limestone and shale) and consumes about 4 GJ of energy in electricity, process heat, and transport (the energy equivalent to 131 cubic meters of natural gas). Moreover, producing one ton of cement generates approximately one ton of CO₂, 3 kg of NOₓ and ~ 0.4 kg of PM10 – an airborne particulate matter that is harmful to the respiratory tract when inhaled. It is estimated [4] that cement contributes ~ 4% of global CO₂ emissions just through the decomposition of limestone, and another 4% from fuel combustion, adding to roughly 8% of global CO₂ production. Therefore, the replacement of cement with other supplementary cementitious materials in concrete mixes is beneficial for the environment.

Table 1: Oxide composition of industrial by-products compared to conventional binders (coal combustion fly ash, converter slag, blast furnace slag and cement).

<table>
<thead>
<tr>
<th>Oxide (% mass)</th>
<th>MSWI bottom ash</th>
<th>Bio-energy fly ash</th>
<th>Paper sludge fly ash</th>
<th>Coal combustion fly ash</th>
<th>Blast furnace slag</th>
<th>CEM I 42.5 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>13</td>
<td>37.7</td>
<td>46.0</td>
<td>4.8</td>
<td>40.6</td>
<td>63.6</td>
</tr>
<tr>
<td>SiO₂</td>
<td>54</td>
<td>27.8</td>
<td>17.7</td>
<td>59.1</td>
<td>36.4</td>
<td>20.5</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>7</td>
<td>9.3</td>
<td>12.1</td>
<td>23.7</td>
<td>13.0</td>
<td>6.2</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>15</td>
<td>6.2</td>
<td>21.8</td>
<td>8.6</td>
<td>9.4</td>
<td>3.6</td>
</tr>
<tr>
<td>MgO</td>
<td>2</td>
<td>3.7</td>
<td>1.6</td>
<td>2.2</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>SO₃</td>
<td>1</td>
<td>15.4</td>
<td>0.8</td>
<td>1.6</td>
<td>0.1</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Using waste products to replace concrete components brings a new dimension besides environmental impact- the sustainability of the material, by reducing the amount of natural raw materials needed. Examples of such replacement materials are recycled concrete aggregates and municipal solid waste incineration bottom ash for the larger particles needed for concrete, and fly ashes, ground granulated blast furnace slags, sludges and recycled concrete fines for the replacement of the cement. One of the drawbacks of using industrial by-products in concrete is the possible introduction of unwanted constituents, like chlorides, sulphates, or some heavy metals. While the latter are known to be either removed through various treatments [5–15] or bound by the cementitious matrix sufficiently, chlorides are the main cause of structural damage in reinforced concrete structures. Therefore, a number of ways in which the environmental impact of concrete production can be reduced become apparent:
1. Employing sustainable energy sources;
2. Incorporating industrial by-products in new concrete recipes;
3. Upgrading recycled concrete as a new building material

These approaches can come together in more ways than one. Alternative energy-generating processes, for instance the incineration of municipal wastes or biomass, also produce materials which can be used as additions in concrete. Intelligent processing of the construction and demolition waste can generate new materials for the production of clinker and also recycled aggregates that can replace the natural gravel in concrete and thus contributing to its sustainability.

**Sustainable energy production**

The macroeconomic survey “bio based economy” performed in the Netherlands concluded that large scale application of biomass for power generation might have a significant environmental benefit and a longer-term positive economic impact of 5 and 8 billion Eur per annum. Biomass is considered a sustainable and renewable resource that can replace fossil fuels like coal and gas. Being a part of the CO₂ cycle, it reduces the CO₂-emission because of its “carbon neutral” origin. Thus, CO₂ released in converting biomass into energy does not contribute to the increase of the greenhouse effect. Therefore, biomass complies with the objective of the government for the reduction of the CO₂ emission and increased independency from fossil fuels. Furthermore, using waste as fuel, instead of using it as landfill, is more favourable for the environment because of preventing the emission of methane from landfills. The landfill generated gas methane is a greenhouse gas which is about 20 times more harmful than CO₂. Therefore, the amount of the land filling with biodegradable waste and hence, the landfill gas emissions are being reduced in recent years. Between 1990 and 2006 the annual emission of landfill methane has decreased by more than 300 kton, from 572 kton methane in 1990 to 257.6 kton in 2006. This corresponds to about 6 Mt CO₂ in equivalent [16].

The Copernicus Institute (Utrecht University), in cooperation with the Agricultural Economics Institute LEI (Wageningen UR), conducted a study on the economic effects of biomass. The survey provides some long-term macroeconomic scenarios for the use of biomass for biofuels, chemistry and electricity generation [17]. The scenarios are designed for situations with high and low amount of biomass imported to the Netherlands from European countries and for situations with high and low levels of technological development. The study encourages the ministry to pursue the scenario of high technology developments in the large-scale import of biomass. The predicted effects of such a scenario by 2030 are: an additional annual turnover of 5 and 8 billion Eur, 25% of the fossil fuels are being replaced by biomass, reducing greenhouse gas emissions by about 25%.

Every year the potential of bio-power plants is increased due to the reasons stated above. According to the recent Energy Report 2011 [18], the Netherlands is less dependent on fossil fuels and gradually switching to renewable energy. Figure 1.1 illustrates the breakdown by source of the total renewable energy production between 1990 and 2010.

The incineration of biomass produces bio-energy fly ashes, which are similar to coal combustion fly ashes, but contain high amounts of chlorides and other contaminants. The incineration of other various waste materials is used to produce energy in the Netherlands. The incineration of paper sludge from the paper recycling industry produces paper sludge fly ash, which can also be considered as concrete ingredient. Municipal solid waste incineration is used on a large scale in the Netherlands and also generates by-products which can be applied in concrete recipes.
Both Portland cement and blended cements are used in the Netherlands, with more than 75% of the total consisting of blended cements (mainly CEM II, CEM III and CEM V). The strength classes produced are 32.5N and R, 42.5N and R and 52.5N and R. Table 1.3 gives the breakdown for cement use in the Netherlands, both locally produced and imported. The most used cement types in this thesis are CEM I 42.5N and CEM I 52.5N, CEM III/B 42.5N which contains 20-34% clinker and 66-80% ground granulated blast furnace slag, according to EN 197-1 [19]. A Cem I fly ash blend containing 21% fly ash is also employed, which is similar to a CEM II/B composition.

Both fly ash and granulated blast furnace slag are being used in construction industry as cement replacement materials and have some common characteristics with Portland cement. For instance, their particle size range is similar to or smaller than that of the Portland cement; they can be involved in the hydration reactions; their chemical compositions are similar to that of Portland cement (Table 1) but with different proportions. Based on the similarities, they can be added to the cement clinker to make fly ash cement or slag cement (Table 2). Moreover, they can be dosed as individual materials directly to the concrete at mixing [20].

There are many types of fly ash produced from different installations:

1. Coal combustion fly ash, from 1882, design Thomas Edison [21];
2. Bio-energy fly ash, since 1971 [22];
3. Paper-sludge fly ash, since 1990 [23];
4. Municipal Solid Waste Incineration (Destructor) fly ash, since 1874 [24].

The current annual production of coal combustion fly ash is about 600 million tons (in 2000) and forms 75-80% of the total ash production worldwide. Only ~ 9% of this production is recycled worldwide [25]. The rest is landfilled, but this is not economically desirable because of high landfill costs, and environmental risks such as leaching to the ground, thereby creating water and also air pollution. However, the government of the Netherlands aimed to reuse the produced coal combustion fly ash from the beginning. This goal was achieved in 1988, when from the annual production of 712400 tons fly ash, 98% was reused. This percentage represents the highest amount in the world [26]. In 2007, 814717 tons of fly ash were produced: 506139 tons of fly ash were used as cement filler and concrete mixtures and 88054 t of fly ash were used in the production of pozzolanic cements. In total, this forms 73% of fly ash production [27].
Table 2: Breakdown of cement types sold in the Netherlands (data from 2008, provided by ENCI BV).

<table>
<thead>
<tr>
<th>Cement type</th>
<th>ENCI BV</th>
<th>Cemex, Dyckerhoff, Holcim, CCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I (95-100% clinker)</td>
<td>1122995</td>
<td>663518 t</td>
</tr>
<tr>
<td>CEM II (65-95% clinker)</td>
<td>92612 t</td>
<td>64928 t</td>
</tr>
<tr>
<td>CEM III (5-64% clinker) Blast furnace slag cement</td>
<td>2053403 t</td>
<td>1079813 t</td>
</tr>
<tr>
<td>CEM V (20-64% clinker)</td>
<td>74901 t</td>
<td>0 t</td>
</tr>
<tr>
<td>Total</td>
<td>3343911 t</td>
<td>1808259 t</td>
</tr>
<tr>
<td></td>
<td>5152170 t</td>
<td></td>
</tr>
</tbody>
</table>

Fly ash can contain various substances; therefore the exact origin of the fly ash is of great influence on its performance when added in the concrete. The European standard EN 450 [28] gives the criteria for the selection of fly ash; only fly ash with certain particle size, (maximum 40% retention on the 45 μm sieve for class N and respectively 12% for class S) and chemical composition and loss on ignition values (under 5% for class A, between 2 and 7% for class B and between 4 and 9% for class C) can be used in concrete production. The ASTM C618 [29] classify fly ash based on the lime content.

Two classifications of fly ash are produced, fly ash type C and type F, where the key difference between these classes is the amount of calcium, silica, alumina, and iron content in the ashes. Class C fly ash contains more than 20% lime, where it is less than 20% in type F fly ash, keeping in mind that the origin and properties of the combustion material are key factors that determine the parameters of the fly ash, and therefore its performance when added to the concrete mixture. Finally, the amount of fly ash determines the class of cement according to the EN 197-1 [19] standard. Fly ash addition to concrete results in increased workability and similar to GGBFS a slow reaction time and increased strength over a long time. Also, the w/c ratio is reduced when fly ash is applied to the concrete mix.

All these effects of using coal combustion fly ash are well researched; however, for other types, such as biomass fly ash and paper sludge fly ash, the route to utilization is not as clear. A first challenge is the lack of standardized requirements for such materials. In the Netherlands, legal requirements for building materials are prescribed from an environmental protection point of view. The effect of these materials as for instance concrete ingredients needs to be studied and quantified before their application.

Leaching standards have been devised for quantifying the emissions of unwanted contaminants from waste materials (EN 12457 [30]). In the Netherlands, there are two legislative documents that regulate the use of waste materials – Landfill Ban Decree [16] and the Soil Quality Regulation [31]. The Landfill Ban Decree classifies waste streams into inert, non-hazardous, hazardous and no landfill materials, according to their emission level. The Soil Quality Regulation uses similar criteria to divide materials destined to be used in the built sector into non-shaped, shaped and IBC materials (which need to undergo insulation, management and control measures).

The use of such materials is legislated in terms of environmental impact, which is quantified by the amount of leached contaminants through a standard test. In order to conform to these legal norms, most of these materials need to undergo pre-processing before being usable as building materials [32–52]. The exception is the paper sludge fly ash, which is mostly contaminant-free, but poses other compositional challenges as an addition in cement-based mixtures.
Table 3: Leaching of building materials requirements according to the Soil Quality Regulation [31].

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Shaped building materials (mg/m²)</th>
<th>Non-shaped building materials (mg/kg)</th>
<th>IBC materials (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sb</td>
<td>8.7</td>
<td>0.32</td>
<td>0.7</td>
</tr>
<tr>
<td>As</td>
<td>260</td>
<td>0.9</td>
<td>2</td>
</tr>
<tr>
<td>Ba</td>
<td>1500</td>
<td>22</td>
<td>100</td>
</tr>
<tr>
<td>Cd</td>
<td>3.8</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>Cr</td>
<td>120</td>
<td>0.63</td>
<td>7</td>
</tr>
<tr>
<td>Co</td>
<td>60</td>
<td>0.54</td>
<td>2.4</td>
</tr>
<tr>
<td>Cu</td>
<td>98</td>
<td>0.9</td>
<td>10</td>
</tr>
<tr>
<td>Hg</td>
<td>1.5</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>Pb</td>
<td>81</td>
<td>2.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Mo</td>
<td>144</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Ni</td>
<td>400</td>
<td>0.44</td>
<td>8.3</td>
</tr>
<tr>
<td>Se</td>
<td>4.8</td>
<td>0.15</td>
<td>3</td>
</tr>
<tr>
<td>Sn</td>
<td>50</td>
<td>0.4</td>
<td>2.3</td>
</tr>
<tr>
<td>V</td>
<td>320</td>
<td>1.8</td>
<td>20</td>
</tr>
<tr>
<td>Zn</td>
<td>800</td>
<td>4.5</td>
<td>14</td>
</tr>
<tr>
<td>Br</td>
<td>670</td>
<td>20</td>
<td>34</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>110000</td>
<td>616</td>
<td>8800</td>
</tr>
<tr>
<td>F⁻</td>
<td>2500</td>
<td>55</td>
<td>1500</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>165000</td>
<td>1.730</td>
<td>20000</td>
</tr>
</tbody>
</table>

Incineration by-products study

A number of treatment options were investigated for each of these materials and their effects characterized through analytical techniques. The final optimized materials were then tested in cement-based mixes. A few of the conclusions of these studies will be summarized here. The bio-energy fly ashes [53–58] were found to have a very different composition than coal combustion fly ash. Besides containing unburnt matter and a large amount of unwanted contaminants (heavy metals and salts such as chlorides and sulphates), their physical properties such as particle size and particle structure are different. A series of treatment steps—unburnt matter removal through air filtering or thermal treatment, washing using several liquid/solid ratios, shaking speeds, temperatures and treatment times, as well as a
separate thermal treatment followed by grinding were analysed for their efficiency. Each of the bio-energy fly ashes was optimized using a combination of these treatment options in order to comply with both the environmental and building materials standards. Applying the final materials in cement-based mixes has shown that this new type of fly ash also presents pozzolanic properties and, when properly treated, can be used as a beneficial addition in mortars.

The investigated paper sludge fly ash comes from an already-optimized burning process that maximizes its potential as addition in concrete mixes [59]. However, its high free lime content implies also a high water demand, which needs to be lowered. Two options for the increase of the use of this material were investigated: lowering its free lime content and blending with other supplementary cementitious materials such as fly ashes and recycled concrete fines. This part of the study brought together the use of a number of the investigated fine materials and has shown the benefit of their mixing in new recipes.

By using different treatment techniques like crushing, thermally and water treating bio-energy fly ash, the materials become comparable with commercial fly ash. Another type of incineration product that is studies is paper sludge fly ash. In this case, the challenges for use in concrete are the increased water demand and content of free lime, which reduce the properties of concrete. It is found that paper sludge fly ash has a positive effect on coal combustion fly ash and can by this increase its own utilization.

In the Netherlands, bottom ash is mainly used as road base material. However, this type of material can also be treated and upgraded into a granulate fraction for use in concrete mixes. Upgrading this type of waste to a new building material is a sustainable approach which leads to lower landfilled quantities of the material as well as reducing the demand for natural aggregates in concrete. In order to obtain a suitable building material from the bottom ash, a complex sequence of treatment steps is necessary. These treatment steps include fractionation, metal recovery (both ferrous and non-ferrous), screening and wet cleaning of the bottom ash into a clean granulate fraction.

Bottom ash is a heterogeneous material, consisting of glass particles, synthetic ceramics fragments, minerals (quartz, calcite, lime, feldspars), paramagnetic and diamagnetic metals and unburnt organic matter. The proportion of these constituents can vary with the particle size and will affect the properties of the final concrete mix. The separation and washing techniques also influence both the particle size and constituent proportions of the MSWI bottom ash.

Various size fractions of bottom ash granulates were studied, with various dimension ranging between 0 and 40 mm. These were further separated into smaller particle ranges, and their chemical and mineralogical composition studied. Leaching tests were performed on different size fractions, along with quantifying the aluminium content. The water content and density of all materials was measured. Based on this information, new concrete recipes were designed and tested for compressive strength [6,60–65]. MSWI bottom ash was successfully applied in both ready-mix and earth-moist concrete recipes. A replacement level of 20% of natural aggregates lead to obtaining kerb stones with even improved flexural strength when compared to the reference recipe. Moreover, normally vibrated concrete recipes with reduced cement content incorporating large amounts of MSWI bottom ash were designed and proven to attain even better mechanical properties than the reference mixtures.

Recycling and reuse of materials

The disposal of wastes can be categorized by environmental impact levels into 6 levels, according to [66]. These levels are, in order starting with the most important: reduce, reuse, recycle, compost, incinerate and landfill. Three most important levels (reduce, reuse, recycle) are referred to as “the 3Rs”. The rates of waste recycling vary greatly across the globe. As it can be seen from Table 4 [67], construction and demolition waste (C&DW) are among the least recycled materials within the European Union, while in the US or Japan the rate of recycling is much (more than 2.5 times) higher.
Table 4: The recycling rate of different materials in Europe, the US and Japan [67].

<table>
<thead>
<tr>
<th>Material</th>
<th>Recycling rate Europe (%)</th>
<th>Recycling rate US (%)</th>
<th>Recycling rate Japan (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete/ C&amp;DW</td>
<td>30</td>
<td>82</td>
<td>80</td>
</tr>
<tr>
<td>Aluminium beverage cans</td>
<td>58</td>
<td>52</td>
<td>93</td>
</tr>
<tr>
<td>Aluminium in buildings</td>
<td>96</td>
<td>N/A</td>
<td>80</td>
</tr>
<tr>
<td>Glass containers</td>
<td>61</td>
<td>22</td>
<td>90</td>
</tr>
<tr>
<td>Lead acid batteries</td>
<td>95</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Paper/cardboard</td>
<td>63</td>
<td>56</td>
<td>66</td>
</tr>
<tr>
<td>PET bottles</td>
<td>39</td>
<td>24</td>
<td>66</td>
</tr>
<tr>
<td>Tires</td>
<td>84</td>
<td>86</td>
<td>85</td>
</tr>
<tr>
<td>Steel containers</td>
<td>66</td>
<td>63</td>
<td>88</td>
</tr>
</tbody>
</table>

When comparing recycled concrete aggregate (RCA) to new aggregate, a number of factors need to be taken into account [67]. A first factor is the land use impact – the use of recycled aggregate means that less waste goes to landfill, while also reducing the need of producing primary aggregates. Another important factor is the transportation cost (including fuel usage and CO₂ emissions), which can be much lower than in the case of new aggregates, if the C&DW is located close to the construction site. New aggregates are usually transported from distant quarries to the construction site. Also to be mentioned are the useful life expectations - using recycled aggregates meaning that the concrete itself has a longer period of use than the structure it was initially part of.

The economic benefits of recycling and minimizing waste volumes are mentioned in [66]:

1. Reducing the volume of materials going to landfills;
2. Free removal of the waste from site;
3. Selling the new recycled products.

Tam [66] also identifies the main reasons for the increase of the volume of demolition concrete waste:

1. Old structures have overcome their use expectancy and need to be demolished;
2. New requirements and necessities lead to the demolition of otherwise still viable structures;
3. Natural destructive phenomena (earthquakes, storms).

In the report on “Recycled concrete” [67] there is a breakdown of C&DW recycling on European countries, between others. Table 3 shows the total C&DW in Mt, the recovered C&DW and the percentage of recovery for these countries. Among the total C&DW recovery, recycled aggregate accounts for 6% to 8% of aggregate use in Europe [67]. The greatest users are the United Kingdom, the Netherlands, Belgium, Switzerland and Germany (data from 2005 and 2006, published in 2008 [67]).

The different sources for recycled concrete aggregate are identified by Oikonomou [68] as either recycled precast elements and cubes after testing or demolished concrete buildings.
the first case, the aggregate should be relatively clean, with only the cement paste adhering to it. In the latter case, the aggregate could be contaminated with salts, bricks and tiles, sand and dust, timber, plastics, cardboard and paper, and metals. It has been shown that even contaminated aggregate, after separation from other waste, and sieving, can be used as a substitute for natural coarse aggregates in concrete.

Table 5: The total and recovered construction and demolition waste (C&DW) in Mt, (N/A= not available) and the percentage of recovery of CD&W [67].

<table>
<thead>
<tr>
<th>Country</th>
<th>Total C&amp;DW (Mt)</th>
<th>Total C&amp;DW Recovery (Mt)</th>
<th>%C&amp;DW Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>14</td>
<td>8</td>
<td>57</td>
</tr>
<tr>
<td>Belgium</td>
<td>14</td>
<td>12</td>
<td>86</td>
</tr>
<tr>
<td>Canada</td>
<td>N/A</td>
<td>8 (recycled concrete)</td>
<td>N/A</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>9 (incl. 3 of concrete)</td>
<td>1 (recycled concrete)</td>
<td>45 (concrete)</td>
</tr>
<tr>
<td>England</td>
<td>90</td>
<td>64</td>
<td>50-90</td>
</tr>
<tr>
<td>France</td>
<td>309</td>
<td>195</td>
<td>63</td>
</tr>
<tr>
<td>Germany</td>
<td>201</td>
<td>179</td>
<td>89</td>
</tr>
<tr>
<td>Ireland</td>
<td>17</td>
<td>13</td>
<td>80</td>
</tr>
<tr>
<td>Japan</td>
<td>77</td>
<td>62</td>
<td>80</td>
</tr>
<tr>
<td>Netherlands</td>
<td>26</td>
<td>25</td>
<td>95</td>
</tr>
<tr>
<td>Norway</td>
<td>N/A</td>
<td>N/A</td>
<td>50-70</td>
</tr>
<tr>
<td>Portugal</td>
<td>4</td>
<td>Minimal</td>
<td>Minimal</td>
</tr>
<tr>
<td>Spain</td>
<td>39</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Switzerland</td>
<td>7 (incl. 2 of concrete)</td>
<td>2</td>
<td>Near 100</td>
</tr>
<tr>
<td>Taiwan</td>
<td>63</td>
<td>58</td>
<td>91</td>
</tr>
<tr>
<td>Thailand</td>
<td>10</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>US</td>
<td>317</td>
<td>127 (recycled concrete)</td>
<td>82</td>
</tr>
</tbody>
</table>
Figure 2: Recycled aggregate fraction of total aggregate use in European countries [67].

The RILEM specifications for RCAs are given in [68]. There are three types of RCAs, depending on their origin:
1. Type I which consists primarily from masonry rubble;
2. Type II which consists primarily from concrete rubble;
3. Type III which consists of a blend of recycled aggregates (max. 20%) and natural aggregates (min. 80%).

BRE Digest 433 specifies similar classes, based on the RILEM categories:
1. RCA (I), origin: brickwork, brick content: 0–100% mass;
2. RCA (II), origin: concrete, brick content: 0–10% mass;
3. RCA (III), origin: concrete and brickwork, brick content: 0–50% mass.

Concrete fractions study

Concrete was crushed using two types of jaw crushers and various crushing steps; the resulting aggregates were sieved into fractions based on the particle sizes. All these fractions were then characterized by their density, thermal treatment reaction, XRD patterns, XRF composition and SEM-EDX images. It was found that the finer the RC fraction is, the less α-quartz they contain. Another observation is that the density of the RCs has a direct correlation with its α-quartz content. The XRF and XRD tests confirmed the decrease of SiO$_2$ content with particle size.

A new method of quantifying the α-quartz content of the samples using the calibrated DSC signal was developed. The method was proven to be accurate by comparing with XRF results, and also following the trend indicated by XRD. The SEM-EDX technique provided further information on the morphology of the particles, which explains the particle size distributions of the finer fraction.
It is shown that the crushing method has a large influence on the quality of the produced materials, and that an optimized crushing method can lead to streams enriched in either cement paste or aggregates [69–74]. A difference in both composition and physical properties is observed for various sizes of crushed concrete. The use of recycled concrete sand in mortar mixtures was proven to be beneficial in terms of mechanical properties, showing good promise for the use of such materials in concrete mixes. When using incineration by-products in the initial concrete recipes, the technique can also be used to concentrate the waste material in certain crushed size fractions, thus enabling the easy size separation of the possibly contaminated fractions and their different recycling route from the cleaner fractions.

**Conclusion**

Several research directions can be identified and combined in order to reduce the environmental impact of concrete and other cement-based products. One such approach is the replacement of Portland cement and natural aggregates by industrial by-products. The focus in this paper was chosen on by-products of the incineration processes, which also have the advantage of producing clean energy- the more sustainable alternative. Such by-products are bio-energy fly ashes from biomass incineration, paper sludge fly ash from the paper recycling process and municipal solid waste incineration ashes. Their application required investigating treatment options for removing certain unwanted contaminants, while at the same time upgrading the properties of these materials for their use in cement-based mixtures. A second approach was considering the reuse of recycled concrete (and thus closing its life cycle) and upgrading its properties through various crushing steps. A method for appraising the quality of the obtained aggregates based on their density and silica content is shortly presented. Such a method can be used to track other constituents in recycled concrete, which would be beneficial for the recycling of concrete incorporating incineration by-products. These methods can be further blended by reusing the obtained aggregates into new cement-based recipes. Treatment steps used for the initial concrete ingredients can be adapted for the recycled aggregates obtained, which can be reused alongside other by-products in new recipes. Such an approach can lead to more sustainable and environmentally-friendly concrete formulations, while at the same time minimising the need for landfilling incineration or industrial by-products.

Figure 3: a. Density (g/cm$^3$) and α-quartz content (%) of all fractions of recycled concrete (RC), presented on a logarithmic scale; b. Relationship between the density and silica content of the calibration points and their corresponding linear fit and those of RC.
References


[40] C.B. Cheah, M. Ramli, The implementation of wood waste ash as a partial cement replacement material in the production of structural grade concrete and mortar: An


